Vivian Loftness
Dagmar Haase
Editors

Sustainable Built Environments

Selected entries from the Encyclopedia of Sustainability Science and Technology

Springer Reference

Sustainable Built Environments

This volume collects selected topical entries from the *Encyclopedia of Sustainability Science and Technology* (ESST). ESST addresses the grand challenges for science and engineering today. It provides unprecedented, peer-reviewed coverage of sustainability science and technology with contributions from nearly 1,000 of the world's leading scientists and engineers, who write on more than 600 separate topics in 38 sections. ESST establishes a foundation for the research, engineering, and economics supporting the many sustainability and policy evaluations being performed in institutions worldwide.

Vivian Loftness and Dagmar Haase (Eds.)

Sustainable Built Environments

With 427 Figures and 65 Tables

Springer

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Bioclimatic Design

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Article Outline

Glossary

Absolute humidity Absolute humidity is defined as the weight of water vapor contained in a unit volume of air. Typical units are pounds of water per pound of dry air or grains of water per cubic foot. Absolute humidity is also known as the water vapor density (D_v).

Celsius temperature (°C) Celsius temperature (°C) refers to temperatures measured on a scale devised in 1742 by Anders Celsius, a Swedish astronomer. The Celsius scale is graduated into 100 units between the freezing temperature of water (0°C) and its boiling point at normal atmospheric pressure (100°C) and is, consequently, commonly referred to as the *centigrade scale.*

Dew-point temperature (DPT) Dew-point temperature (DPT) is the temperature of a surface upon which water vapor contained in the air will condense into liquid water. Stated differently, it is the temperature at which a given quantity of air will become saturated (reach 100% relative humidity) if chilled at constant pressure. It is thus another indicator of the moisture content of the air. Dew-point temperature is not easily measured directly; it is conveniently found on a psychrometric chart if dry-bulb and wet-bulb temperatures are known.

Dry-bulb temperature (DBT) Dry-bulb temperature (DBT) is the temperature measured in air by an ordinary (dry bulb) thermometer and is independent of the moisture content of the air. It is also called "sensible temperature."

Fahrenheit temperature (F) Fahrenheit temperature (F) refers to temperature measured on a scale devised by G. D. Fahrenheit, the inventor of the alcohol and mercury thermometers, in the early eighteenth century. On the Fahrenheit scale, the freezing point of water is 32°F and its boiling point is 212°F at normal atmospheric pressure.

Humidity Humidity is a general term referring to the water vapor contained in the air. Like the word "temperature," however, the type of "humidity" must be defined.

Relative humidity (RH) Relative humidity (RH) is defined as the percent of moisture contained in the air under specified conditions compared to the amount of moisture contained in the air at total saturation at the same (dry-bulb) temperature. Relative humidity can be computed as the ratio of existing vapor pressure to vapor pressure at saturation, or the ratio of absolute humidity to absolute humidity at saturation existing at the same temperature and barometric pressure.

Water vapor pressure (P_v) Water vapor pressure (P_v) is that part of the atmospheric pressure exerted due to the amount of water vapor present in the air. It is expressed in terms of absolute pressure as inches of mercury (in. Hg) or pounds per square inch (psi).

Wet-bulb temperature (WBT) Wet-bulb temperature (WBT) is an indicator of the total heat content (or enthalpy) of the air, that is, of its combined sensible and latent heats. It is the temperature measured by a thermometer having a wetted sleeve over the bulb from which water can evaporate freely.

Definitions

Bioclimatic design – combining "biology" and "climate" – is an approach to the design of buildings and landscape that is based on local climate. The

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approach was promoted in a series of professional and popular publications in the 1950s [1, 2]. In using the term "bioclimatic," architectural design is linked to the physiological and psychological need for health and comfort. In adopting bioclimatic approaches, the designer endeavors to create comfort conditions in buildings by understanding the microclimate and resulting design strategies that include natural ventilation, daylighting, and passive heating and cooling. The premise of bioclimatic design is that buildings utilize natural heating, cooling, and daylighting in accordance with local climatic conditions.

Resilient design is an extension of bioclimatic design. It adds precautionary measures to provide health and safety to prepare for natural disasters, including extreme storms and flooding of inland watersheds and coastal areas. The concept of resiliency applies lessons from natural systems to design for extreme conditions using strategies found in natural systems, such as buffering, zone separation, redundancy, rapid feedback, and decentralization.

Introduction

Bioclimatic design had been part of practical knowledge of indigenous building throughout historical periods, including early modern architecture. When air-conditioning systems became widely available at the end of the 1950s, interest in bioclimatic design became less evident in professional and popular literature and in built work. The topic reemerged in response to energy shortages of the 1970s – when "passive solar design" became the popular term to describe the approach, at first emphasizing solar heating but soon broadened to passive cooling and daylighting.

With the emergence of global environmental concerns of the 1990s – recognizing that energy conservation has "cascading" effects and benefits in reducing pollution and in mitigating global warming – the scope of bioclimatic design was enlarged to include landscape, water, and waste nutrient recovery. *Sustainable design* of architecture and communities emerged as an approach to protect and improve the biological health of communities conceived as the ecology of building, site, and region.

Some bioclimatic design techniques – earth sheltering is an example – can contribute to comfort and reduce both heating and cooling loads year round. Other techniques are useful only part of the year. The effectiveness of passive solar heating, for example, is very specific to the need for heating and otherwise needs to be tempered by sun shading and thermal mass. Natural ventilation can provide comfort in all seasons, especially in summer when it can reduce or eliminate the need for air-conditioning in some climates.

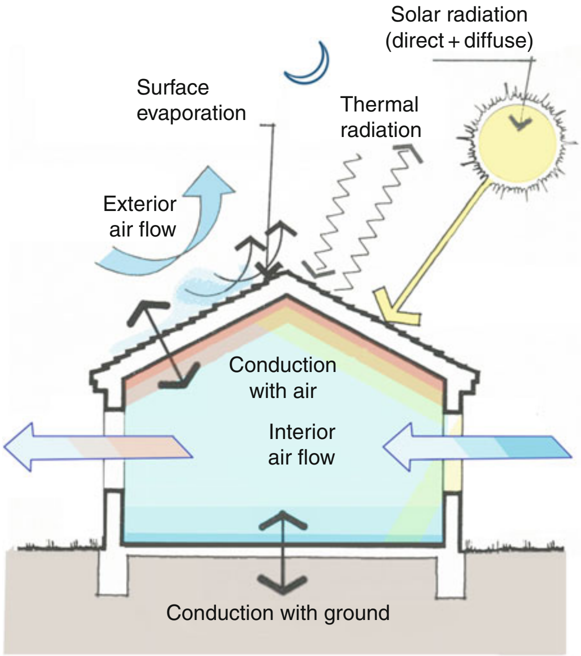
All buildings experience interruptions of conventional energy availability, often coincident with weather extremes and natural disasters. A precautionary approach to the design of all buildings is to provide bioclimatic means to insure subsistence levels of heating, cooling, and daylighting for comfort, health, and safety in case all power sources are interrupted. For the longer term, in which conventional energy shortages and emergencies are unpredictable, buildings without natural heating, cooling, and lighting impose serious liabilities on occupants and owners.

Strategies of Bioclimatic Design

Bioclimatic design strategies are effective for "envelope-dominated" structures – such as homes and one- or two-story facilities – to provide a large portion if not all of the energy required to maintain comfort conditions.

"Internal load dominated" buildings – such as hospitals, offices, commercial kitchens, and windowless stores – experience high internal gains imposed by the heat of occupancy, lights, and equipment. In such cases, the external climatic conditions may have less influence on achieving comfort and low energy utilization. However, as internal loads are reduced through energy-efficient design – such as low-wattage lighting, energy-efficient equipment, occupancy scheduling and zoning – the effects of climate become more obvious and immediate. All buildings can benefit from available daylighting, but large glazed areas require careful shading control, glazing selection, and possibly night insulation.

The "resources" of bioclimatic design are the natural flows of energy in and around a building – created by the interaction of sun, wind, precipitation, vegetation, temperature, and humidity in the air and in the ground. In some instances, this "ambient energy" is useful immediately or can be stored for later use. There are definable "pathways" by which heat is gained or lost between the interior and the external climate in



Bioclimatic Design. Figure 1
Paths of energy exchange at the building microclimate scale. Bioclimatic design is based upon understanding energy flows within and around buildings (Watson and Labs [13])

terms of the classic definitions of heating energy transfer mechanics. From these, the resulting bioclimatic design strategies can be defined (Fig. 1 and Table 1).

- *Conduction* – from hotter objects to cooler objects by direct contact.
- *Convection* – by flow of air between warmer objects and cooler objects.
- *Radiation* – from hotter objects to cooler objects within the direct view of each other regardless of the temperature of air in between, including radiation from sun to earth.
- *Evaporation* – the change of phase from liquid to gaseous state: The sensible heat (dry-bulb temperature) in the air is lowered by the latent heat absorbed from air when moisture is evaporated.
- *Thermal storage* – from heat charge and discharge both diurnally and seasonally, as a function of its specific heat, mass, and conductivity. Although not usually listed alongside the four classic means of heat transport, this role of thermal storage is helpful in understanding the heat transfer physics of building climatology.

In winter (or underheated periods), the objectives of bioclimatic design are to resist loss of heat from the

Bioclimatic Design. Table 1 Strategies of bioclimatic design (Watson and Labs [13])

Bioclimatic design strategy	Predominant season[a]	Process of heat transfer: Conduction	Convection	Radiation	Evaporation
Minimize conductive heat flow	Winter and summer[b]	√			
Delay periodic heat flow	Winter and summer	√		√	
Minimize infiltration	Winter and summer[b]		√		
Provide thermal storage[c]	Winter and summer	√	√	√	
Promote solar gain	Winter			√	
Minimize solar gain	Summer			√	
Minimize external air flow	Winter		√		
Promote ventilation	Summer		√		
Promote radiant cooling	Summer			√	
Promote evaporative cooling	Summer				√

[a]Properly described as "underheated" and "overheated"
[b]In overheated periods where air-conditioning is required
[c]Thermal storage may utilize "phase change" materials and the latent heat capacities of chemicals such as eutectic salts

building envelope and to promote gain of solar heat. In summer (or overheated periods), these objectives are the reverse, to resist solar gain and to promote loss of heat from the building interior. The strategies can be set forth as:

- *Minimize conductive heat flow.* This strategy is achieved by using insulation. It is effective when the outdoor temperature is significantly different, either lower or higher, than the interior comfort range. In summer, this strategy should be considered whenever ambient temperatures are within or above the comfort range and where natural cooling strategies cannot be relied upon to achieve comfort (i.e., whenever mechanical air-conditioning is necessary).
- *Delay periodic heat flow.* While the insulation value of building materials is well understood, it is not as widely appreciated that building envelope materials also can delay heat flows that can be used to improve comfort and to lower energy costs. Time lag through masonry walls, for example, can delay the day's thermal impact until evening and is a particularly valuable technique in hot arid climates with wide day-night temperature variations. Techniques of earth sheltering and berming also exploit the long-lag effect of subsurface construction.
- *Minimize infiltration.* "Infiltration" refers to uncontrolled air leakage around doors and windows and through joints, cracks, and faulty seals in the building envelope. Infiltration (and the resulting "exfiltration" of heated or cooled air) is considered the largest and potentially the most intractable source of energy loss in a building, once other practical insulation measures have been taken.
- *Provide thermal storage.* Thermal mass inside of the insulated envelope is critical to dampening the swings in air temperature and in storing heat in winter and as a heat sink in summer.
- *Promote solar gain.* The sun can provide a substantial portion of winter heating energy through elements such as equatorial-facing windows and greenhouses that include other passive solar techniques which utilize spaces to collect, store, and transfer solar heat.
- *Minimize solar gain.* The best means for ensuring comfort from the heat of summer is to minimize the effects of the direct sun by shading windows from the sun, or otherwise to minimize the building surfaces exposed to the summer sun by use of radiant barrier and by insulation.
- *Minimize external air flow.* Winter winds increase the rate of heat loss from a building by "washing away" heat and thus accelerating the cooling of the exterior envelope surfaces by conduction, and also by increasing infiltration (or more properly, exfiltration) losses. Siting and shaping a building to minimize wind exposure or providing windbreaks can reduce the impact of such winds.
- *Promote ventilation.* Cooling by air flow through an interior may be propelled by two natural processes, cross-ventilation (wind driven) and stack-effect ventilation (driven by the buoyancy of heated air even in the absence of external wind pressure). A fan (using photovoltaic for fan power) can be an efficient way to augment natural ventilation cooling in the absence of sufficient wind or stack-pressure differential.
- *Promote radiant cooling.* A building can lose heat effectively if the mean radiant temperature of the materials at its outer surface is greater than that of its surroundings, principally the night sky. The mean radiant temperature of the building surface is determined by the intensity of solar irradiation, the material surface (film coefficient), and by the emissivity of its exterior surface (its ability to "emit" or reradiate heat). This contributes only marginally, if the building envelope is well insulated.
- *Promote evaporative cooling.* Sensible cooling of a building interior can be achieved by evaporating moisture into the incoming air stream (or, if an existing roof has little insulation, by evaporative cooling the exterior envelope such as by a roof spray). These are simple and traditional techniques and most useful in hot-dry climates if water is available for controlled usage. Mechanically assisted evaporative cooling is achieved with an economizer-cycle evaporative cooling system, instead of, or in conjunction with, refrigerant air-conditioning.

Bioclimatic Analysis

Analysis of climatic data is a first step in bioclimatic design. Preliminary design direction and rules of thumb can be determined by graphing bioclimatic data. While the method can be done by hand, computer-assisted methods allow this approach to be increasingly accurate.

Humans are comfortable within a relatively small range of temperature and humidity conditions, roughly between 68°F and 80°F (20–26.7°C) and 20–80% relative humidity (RH), referred to on psychrometric charts as the "comfort zone." These provide a partial description of conditions required for comfort. Other variables include environmental indices – radiant temperature and rate of airflow – as well as clothing and activity (metabolic rate). While such criteria describe relatively universal requirements in which all humans are "comfortable," there are significant differences in and varying tolerance for discomfort and conditions in which stress is felt, depending on age, sex, health, cultural conditioning, and expectations.

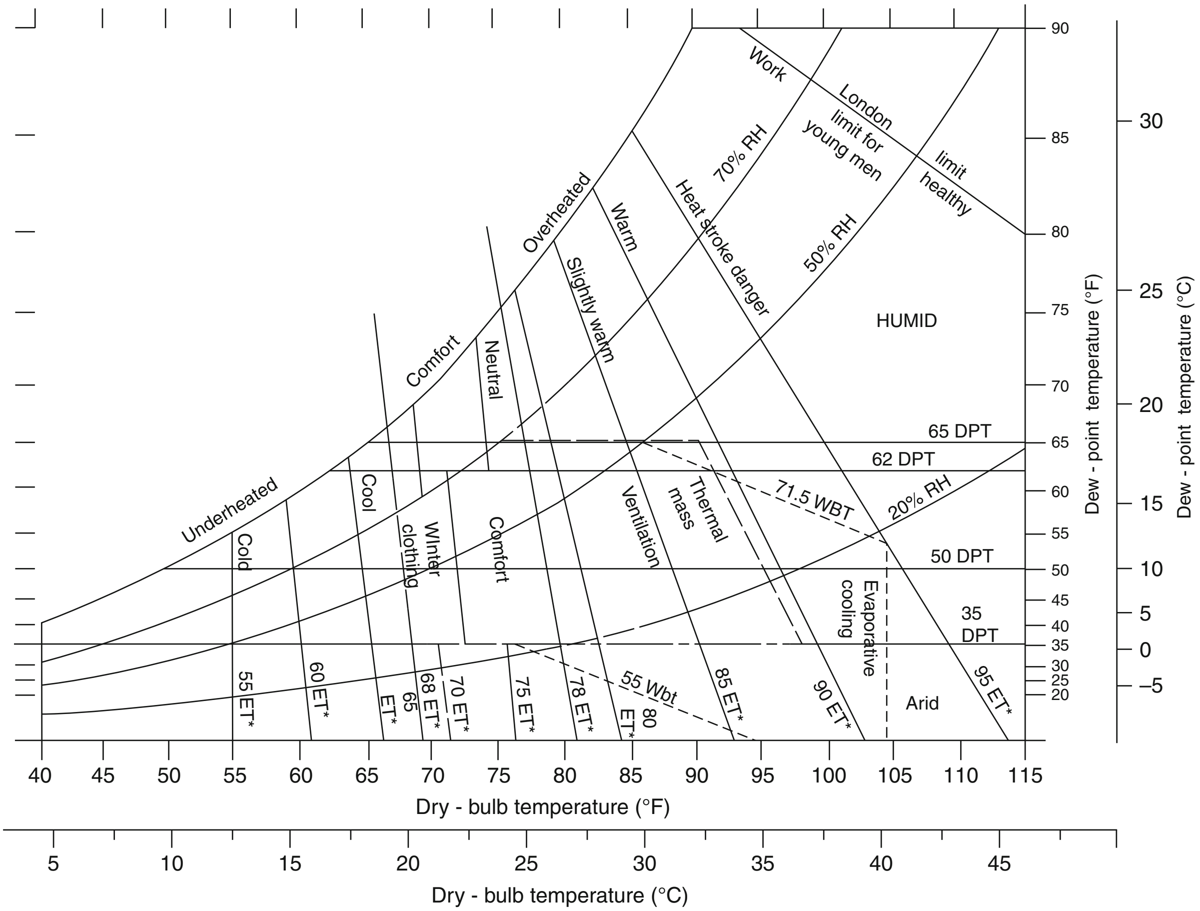
Givoni [3] and Milne and Givoni [4] proposed a design method using the building bioclimatic chart, modified by Arens [5] (Fig. 2). The chart adopts the psychometric format, overlaying it with parameters for the appropriate bioclimatic design techniques to create human comfort in a building interior. If local outdoor temperatures and humidity fall within specified zones, the designer is alerted to opportunities to use specific bioclimatic design strategies to create effective interior comfort.

Computer-based simulation and energy design tools make it possible to utilize site-specific hourly weather data to analyze data for bioclimatic design. This makes it possible to compare bioclimatic design strategies for a given climate, comparing a proposed design with a "base case," that is, the same building without a proposed design feature, such as south-facing glass, added insulation, shading, ventilation, and thermal mass.

Figure 3 depicts a simulated "representative winter week" (7 days) comparison of a "base case" house with a combined set of options, including solar-oriented windows (while decreasing windows on other orientations), increased insulation including nighttime curtains, and interior thermal mass. The "base case" house represented the US code-compliant national average construction, published by the National Association of Home Builders. Bioclimatic design strategies were added as achievable within a 5% increase in construction cost. The "representative winter week" represented a 30-year average winter week (November to January) in which 3 days of clouds were followed by 3 days of sunshine. Heat gains in Btu are indicated above the horizontal bars, and losses below it. The illustration indicates the benefit of the "solar pulse," that is, passive solar gain in the 3 sunny days at the end of the 7 days (lower right), compared to negligible solar benefit in the Base case during the same sunny period (upper right). In this particular week, the combined passive strategies accomplished a 38% in energy requirement.

The example in Fig. 3 was part of a research project that compared a variety of bioclimatic features, singly and together, in 20 US cities [6]. The results supported several conclusions. Firstly, the relative effectiveness of any particular bioclimatic design technique is more than additive, that is, when combined they supported larger efficiencies in performance than when used singly. Secondly, when compared in different climatic zones, the rank order of most effective strategies changed – perhaps obvious, but worthy as confirmation that each climatic region has its own most appropriate design techniques. But finally, the difference between one top strategy and another was for the most part not so far ahead of others that there is any one answer. Designers have a choice, within a set of high performing strategies and techniques.

These findings are supported by a selective tabulation (Table 2), with results of the 20 city comparisons (simulated for a full year, compiling TMY data as available in 1984). For the four cities shown in Table 2, representatives of different US climates, the heating energy requirement is shown in blue and cooling in red. The "boxed" option indicates the most effective technique for combined heating and cooling energy for each location. In the case of Boston, the passive solar and super-insulation options are approximately equal and either one represents a 40% reduction of energy required compared to the base house. The



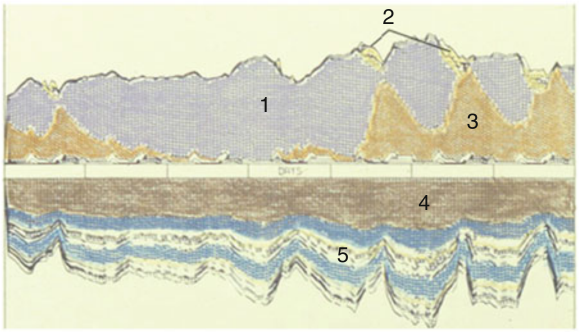
Bioclimatic Design. Figure 2

Building bioclimatic chart. The chart indicates parameters of local climatic conditions favorable for bioclimatic design strategies (Based on Givoni [3] and Arens [5])

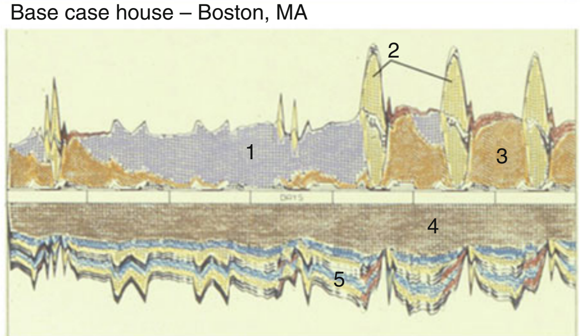
same strategies achieved more that 46% reduction in Seattle, 62% in Los Angeles, whereas none of the solar options outperformed an 18% improvement achieved simply outside insulated block walls in New Orleans. While such results are "imagined," that is, the result of assumptions made in computation, they indicate the value of simulation to help understand the thermodynamics of climate, building design options, and resulting comfort and energy requirements.

Climatic data for computer simulation for locations worldwide are available on the Web. In regions of the world where extensive climatic data are not available and where, for example, data are limited only to monthly averages of temperature and humidity, the available data may not be coincident and must be interpreted with caution.

TMY summaries contain simultaneous climatic data for all 8,760 h in a "typical" year. Available for airport locations, mostly in the United States, each file contains one complete year of hourly data, including direct (beam) solar radiation, total horizontal solar radiation, dry-bulb temperature, dew-point humidity, wind speed, and cloud cover. Electronic files of climatic data for most US locations (major airports) are available through various sources on the Web from NREL [7]. Over 500 stations worldwide are available on the energy plus Web site [8].



Base case house – Boston, MA



Base case w/ passive solar, insulation, shading

Bioclimatic Design. Figure 3
Simulation of bioclimatic design features. The simulation illustrates the energy performance of passive solar strategies compared to a base case in Boston, MA, climate (cool/temperate, partly sunny). (1) Heating energy required, (2) passive solar contribution, (3) thermal mass contribution, (4) roof heat loss, (5) heat loss various other surfaces (Watson and Harrington 1979. Unpublished manuscript)

Several papers by Arens [9, 10] describe techniques to interpolate multiple TMY3 data sets for locations "in between" airport locations to adjust them to match substation monthly means, or modify them further to account for the building-site surroundings.

Climate consultant is a computer-based program that can be downloaded at no cost from the Web [11]. Part of a career-long project of UCLA Professor Emeritus Murray Milne to develop public domain energy design tools [12], the software plots weather data, including temperatures, wind velocity, sky cover, percent sunshine, and beam and horizontal irradiation. It uses these data to create psychometric charts and plots hourly data in the above-mentioned zones that indicate timetables of bioclimatic needs, sun charts showing times of solar needs and shading requirements. It includes 3-D plots of temperature, wind speed, and related climatic data cross-referenced to bioclimatic design practices presented in Watson and Labs [13].

Figure 4 represents a typical bioclimatic chart generated by Climate Consultant. It displays an annual summary for Minneapolis and in the upper left, the percent (hours per year) that bioclimatic categories are effective.

Bioclimatic Design Practices

Each locale has its own bioclimatic profile, sometimes evident in indigenous and long-established building practices. Bioclimatic design techniques can be set forth as a set of design opportunities (adapted from Ref. [9]):

- *Wind breaks* (winter) – Two design techniques serve the function of minimizing winter wind exposure:
  - Use neighboring landforms, structures, or vegetation for winter wind protection.
  - Shape and orient the building shell to minimize winter wind turbulence (Fig. 5).
- *Thermal envelope* (winter) – Isolating the interior space from the hot summer and cold winter climate, such as:
  - Use attic space as buffer zone between interior and outside climate.
  - Use basement or crawl space as buffer zone between interior and grounds.
  - Use vestibule or exterior "wind-shield" at entryways.
  - Locate low-use spaces, storage, utility, and garage areas to provide climatic buffers.
  - Subdivide interior to create separate heating and cooling zones.
  - Select insulating materials for resistance to heat flow through building envelope.
  - Apply vapor barriers to the warm side of building envelope assemblies to control moisture migration.
  - Develop construction details to minimize air infiltration and exfiltration.
  - Provide insulating controls at glazing.

Bioclimatic Design. Table 2 *Comparison of bioclimatic options in four US climates.* Requirements for heating (in blue) and cooling (in red) are compared for an identical "base case" house (code compliant). Different strategies are compared in representative US climates (Watson and Harrington [6])

	Base case[a]	Earth berms[b]	Trombe wall[c]	Block wall[d]	Passive solar[e]	Super insul.[f]
Boston	39.0[g] 5.2[h]	36.1 4.8	25.2 6.6	36.8 3.4	20.0 6.6	19 7.4
New orleans	4.4 15.9	3.9 15	.7 21.4	1.6 15.2	1.1 17.7	1.0 18.9
Los angeles	6.3 2.4	5.6 2.4	.3 3.0	1.8 2.0	.8 3.3	.7 3.6
Seattle	28.8 1.5	26.5 1.4	20.4 1.6	26.8 .5	16.4 1.7	11.5 2.3

All cases have shading and natural ventilation to reduce cooling load

[a]Base case R13 walls, R20 roof, 12% glazing

[b]Earthberms 4 ft. high on E, N, and W walls

[c]Trombe wall 12″ concrete w/R5 nightshade unvented

[d]Block wall insulated on exterior

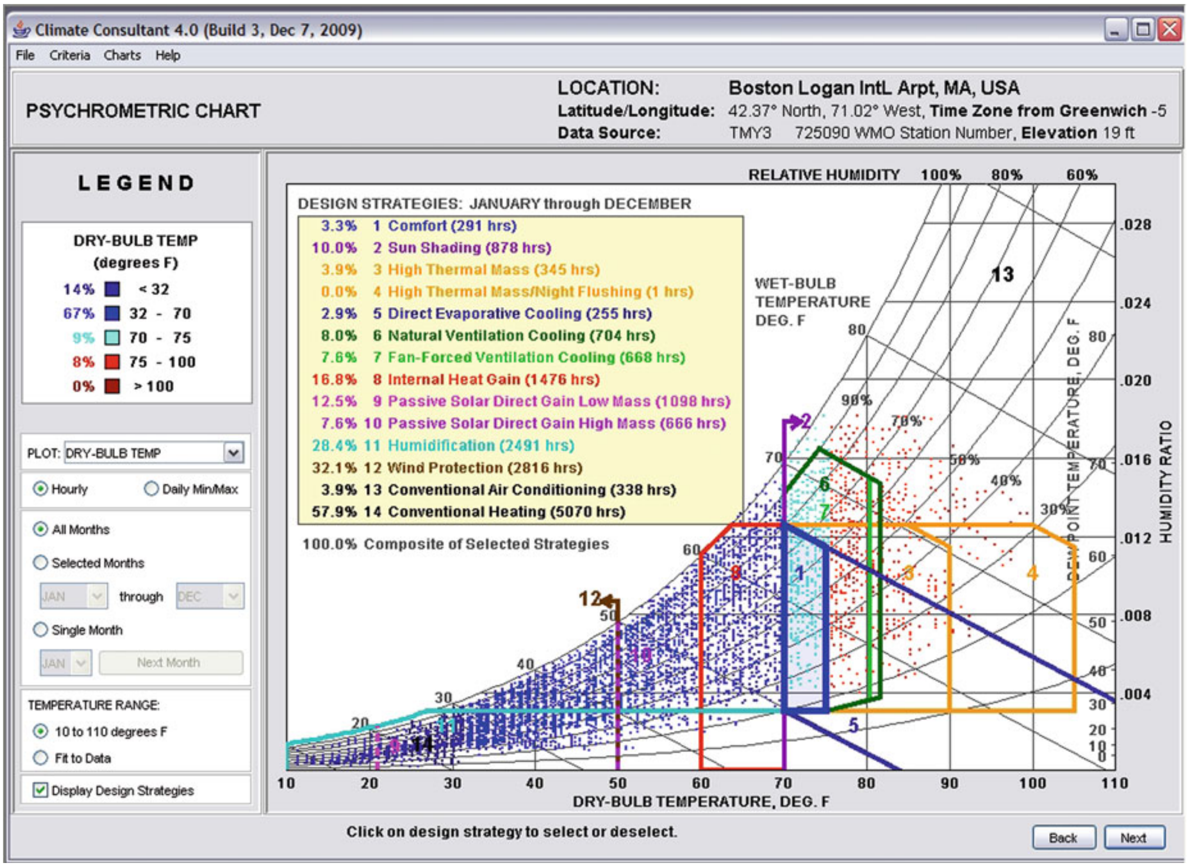
[e]Passive solar R20 walls, R3o ceiling, 24% glazing, R5 nightshade

[f]Super-insulation R40 walls, R50 roof, R5 nightshade

[g]Heating energy required in Btu

[h]Cooling energy required in Btu

  - Use heat-reflective (or radiant) barriers on (or below) surfaces oriented to the summer sun.
  - Minimize the outside wall and roof area ratio of exterior surface to enclosed volume (Fig. 6).
- *Solar windows and walls* (winter) – Using the winter sun for heating a building through solar-oriented windows and walls is provided by a number of techniques:
  - Maximize reflectivity of ground and building surfaces outside windows facing the winter sun.
  - Shape and orient the building shell to maximize exposure to the winter sun.
  - Use high-capacitance thermal mass materials in the interior to store solar heat gain.
  - Use solar wall and roof collectors on equatorial-oriented faces.
  - Optimize the area of equatorial-facing glazing.
  - Use clerestory skylights for winter solar gain and natural illumination.
  - Provide solar-oriented interior zone for maximum solar heat gain, with solar control for shading in overheated periods (Fig. 7).
- *Indoor/outdoor rooms* (winter and summer) – Courtyards, covered patios, seasonally screened and glassed-in porches, greenhouses, atriums, and sun spaces can be located in the building plan for summer cooling and winter heating benefits:
  - Provide outdoor semi-protected areas for year-round climate moderation (Fig. 8).
- *Earth sheltering* (winter and summer) – Techniques such as banking earth against the walls of a building or covering the roof, or building a concrete floor on the ground, have a number of climatic advantages for thermal storage and damping temperature fluctuations (daily and seasonally), providing wind protection and reducing envelope heat loss or gain (winter and summer). These techniques are often referred to as earth-contact or earth-sheltering design:



Bioclimatic Design. Figure 4

Climate consultant display of the building bioclimatic chart for Albany, NY. Climate Consultant provides visual displays of the Building Bioclimatic Chart, along with a wide range of other climatic data analyses (Milne and Li [12]) Climate Consultant Web link http://www.energy-design-tools.aud.ucla.edu/

- Use slab-on-grade construction for ground temperature heat exchange and thermal storage.
- Use earth-covered or sod roofs.
- Recess structure below grade or raise existing grade for earth sheltering (Fig. 9).

- *Thermally massive construction* (summer and winter) – Particularly effective in hot arid zones, or in more temperate zones with cold clear winters. Thermally massive construction provides a "thermal fly wheel." Absorbing heat during the day from solar radiation and convection from indoor air can create comfort if it is cooled at night, if necessary through nighttime ventilative cooling (if air temperatures fall within the comfort zone):
  - Use high mass construction with outside insulation and nighttime ventilation techniques in summers.
  - For selected climates (hot dry), select high-capacitance materials to dampen heat flow through the building envelope (Fig. 10).
- *Sun shading* (summer) – Because midday solar altitude angles are much higher in summer than in winter, it is possible to shade windows from the sun during the overheated summer period while allowing it to reach the window surfaces and

Bioclimatic Design. Figure 5
Sea Ranch, California. Landscape planting, roof slopes, and fencing designed for wind protection. Esherick, Homsey, Dodge, and Davis, Architects and Planners with Lawrence Halprin, Landscape Architect

spaces in winter. Providing summer sun shading does not need to conflict with winter solar heat gain:
- Minimize reflectivity of ground and building surfaces outside windows facing the summer sun.
- Use neighboring landforms, structures, or vegetation for shading the summer sun.
- Shape and orient the building shell to minimize exposure to the summer afternoon sun.
- Provide seasonally operable shading, including deciduous trees.

- *Natural ventilation* (summer and seasonal)–Natural ventilation is a simple concept by which to cool a building:
  - Shape and orient the building shell to maximize exposure to summer breezes.
  - Use an "open plan" interior to promote airflow.
  - Provide vertical airshafts to promote "thermal chimney" or stack-effect airflow.
  - Use double roof construction for ventilation within the building shell.
  - Orient door and window openings to facilitate natural ventilation from prevailing summer breezes.
  - Use wing walls, overhangs, and louvers to direct summer wind flow into the interiors.
  - Use louvered wall openings for maximum ventilation control.
  - Use roof monitors for "stack-effect" ventilation (Fig. 11).
- *Plants and water* (summer) – Several techniques provide cooling by the use of plants and water near building surfaces for shading and evaporative cooling:
  - Use planting next to building skin (provided it does not interfere with ventilation).
  - Use roof spray or roof ponds for evaporative cooling.
  - Use ground cover and planting for site cooling.
  - Maximize on-site evaporative cooling (Fig. 12).

The Importance of Documenting Performance

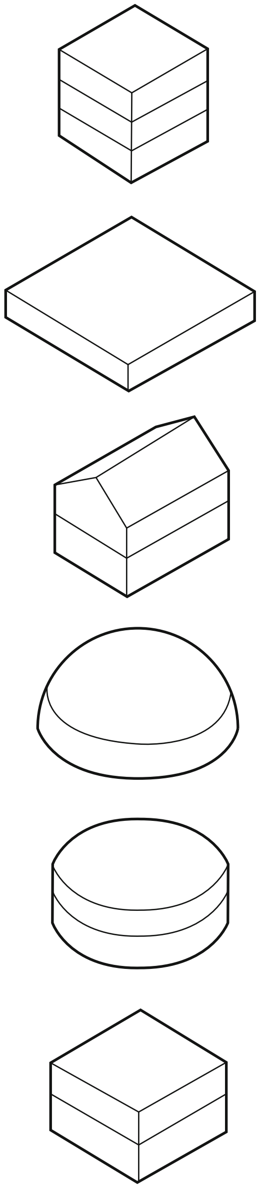
Simulation is a design tool, most appropriately used during the early design phases when alternate design techniques are considered. Simulation is not necessarily a means to predict actual performance. Design knowledge requires post-occupancy evaluation after a building is built and occupied.

To compare performance with predesign-simulated expectations requires careful monitoring of on-site weather conditions. Variations of use, user behavior, and factors as simple as how operating temperature controls are adjusted will account for greater variation than climate alone.

A post-occupancy survey was undertaken to assess 84 solar homes built with the assistance of a Solar Grant Program in Connecticut [14]. A grant of $5,000 was offered to assist owners of existing homes to retrofit solar features, or, to incorporate into new construction. Solar features could include south-facing windows and skylights, thermal mass (Trombe wall), sunspace, and window insulation, as well as active solar domestic hot water systems. The survey asked what problems were notable after 1–5 years of occupancy, and of these what problems could be corrected and what could not (Table 3).

Bioclimatic Design of Atriums and Wintergardens

Atriums offer many energy design opportunities, depending upon climatic resources, to provide natural heating, cooling, lighting, and plants. It is necessary to



Total volume	=	32,000	
Surface area	=	5,039	SVR = 0.157
3rd Floor	=	1,007	
2ND Floor	=	1,007	
Base area	=	1,007	SFAR = 5.0
Combined area	=	3,021	SFAR = 1.67
Total volume	=	32,000	SVR = 0.17
Surface area	=	5,429	
Floor area	=	3,200	SFAR = 1.7
Total volume	=	32,000	
Surface area	=	4,754	SVR = 0.148
Upper floor	=	1,350	
Base area	=	1,350	
Combined area (includes attic)	=	2,700	SFAR = 1.76
Total volume	=	32,000	
Surface area	=	3,864	SVR = 0.12
Upper floor	=	1,618	
Base area	=	1,932	SFAR = 2.0
Combined area	=	3,550	SFAR = 1.09
Total volume	=	32,000	
Surface area	=	4,435	SVR = 0.138
Upper floor	=	1,600	
Base area	=	1,600	SFAR = 2.77
Combined area	=	3,200	SFAR = 1.38
Total volume	=	32,000	
Surface area	=	4,800	SVAR = 0.15
Upper floor	=	1,600	
Base area	=	1,600	SFAR = 3.0
Combined area	=	3,200	SFAR = 1.5

Bioclimatic Design. Figure 6
Analysis of building aspect ratio. Simplified building shapes are compared for ratio of exterior surface to enclosed volume (Watson and Labs [13])

establish clear design goals, defining the opportunities and liabilities of solar heating, natural cooling, and daylighting choices. Provisions for healthy planting and indoor gardens can be combined with atrium design, which enlarges the design criteria to include healthy conditions for plants as well as people.

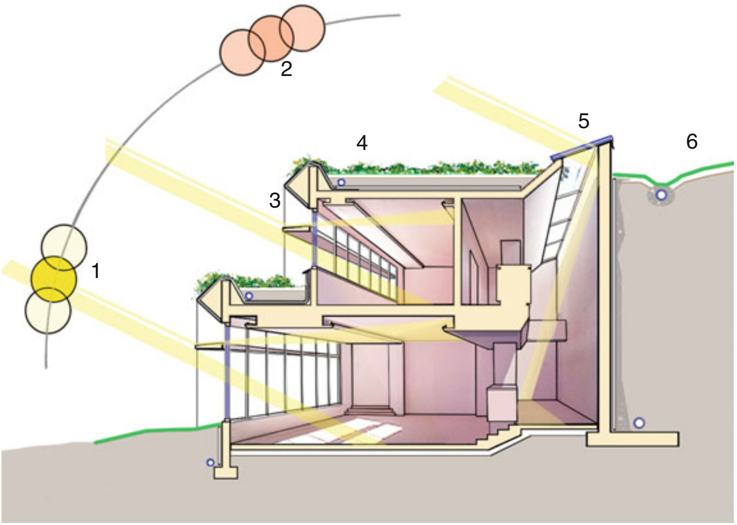
The atrium concept of climate control has been used throughout the history of architecture and in indigenous building in all climates of the globe. Suggested by its Latin meaning as "heart" or an open courtyard of a Roman house, the term "atrium" as used today is a protected courtyard or glazed winter garden placed within a building. Modern atrium

Bioclimatic Design. Figure 7
Solar windows walls. Keck + Keck, Architects developed solar design principles in the Chicago area in the 1930s. The solar home designs of Keck + Keck – in this example a prototype prefab homes for Green Ready-Built Homes – included large south-facing glass, exposed masonry floors with hypostyle (warm air radiant) heating, interior masonry walls, interior curtains, and exterior shading (Photo: William Keck, Architect)

Bioclimatic Design. Figure 8
Protected courtyard. Buli Khelam Ihakhang Monastery, Bhutan. In the Himalayan tradition of building, an enclosed courtyard with sun exposed adobe walls and windows creates a wind-protected microclimate, permitting a temperate planting regime to flourish within, in contrast to high mountain climatic conditions of its locale (Photo: Donald Watson)

design incorporates many architectural elements – wall enclosures, sun-oriented openings, shading and ventilation devices, and subtle means of modifying temperature and humidity – suggested by examples that derive from the courtyard designs of Roman, early Christian, and Islamic buildings, and the nineteenth-century greenhouses and glass-covered arcades of Great Britain and France.

a



1 Winter solstice 3 Light shelf daylight reflector 5 Skylight
b 2 Summer solstice 4 Green roof 6 Earthsheltering

Bioclimatic Design. Figure 9
(**a**) *Earth-covered home.* New Canaan CT, USA. 1986. The design combines south-facing windows with light shelves to extend daylighting and provide summer shading, skylighting, and earth sheltering (Photo: Donald Watson, FAIA, Architect). (**b**) *Cross-section earth-covered home.* The cross-section of the earth-covered home was designed to provide balanced daylighting throughout the year, accomplished by light shelves and a clerestory light well

Atriums offer many energy design opportunities: first, comfort is achieved by gradual transition from outside climate to building interior; second, designed properly, protected spaces and buffer zones create natural and free-flowing energy by reducing or by eliminating the need to otherwise heat, cool, or light building interiors. Depending on climatic resources and building use, the emphasis in atrium design has to be balanced between occupancy and comfort criteria and the relative need for heating, cooling, and/or lighting.

How the atrium can work as an energy-efficient modifier of climate is best seen by examining separately its potential for natural heating, cooling, and lighting.

The first step is to establish a clear set of energy design goals appropriate to the specific atrium design. The resulting solution will depend upon its program (whether for circulation only or for longer term and sedentary human comfort and/or for plant propagation and horticultural display) and the resulting environmental control requirements.

Bioclimatic Design. Figure 10
Thermal mass appropriate for hot-dry climate. Indigenous adobe block construction, with roof and window overhangs to shade and protect the walls. Tahono O'Odham Nation, Papago Indian Reservation, Arizona (Photo: Donald Watson)

Solar Heating

If heating efficiency alone is the primary energy design goal of the atrium, the following design principles should be paramount:

H1 – To maximize winter solar heat gain, orient the atrium aperture (openings and glazing) to the equator. If possible, the glazing should be vertical or sloped not lower than a tilt angle equal to the local latitude.

H2 – To store and distribute heat, place interior masonry directly in the path of the winter sun. This is most useful if the heated wall or floor surface will in turn directly radiate to building occupants.

H3 – To prevent excessive nighttime heat loss, consider an insulating system for the glazing, such as insulating curtains or high performance multilayered window systems.

Bioclimatic Design. Figure 11
Shading and ventilation strategies. Built in an era well before air-conditioning, plantation manor houses such as the 1827 San Francisco Plantation House, New Orleans, combined a range of strategies for natural cooling in hot humid climates zones, including open understory and porches, cross-ventilation, and roofs designed to induce ventilation by thermal updraft (Photo: Robert Perron)

Bioclimatic Design. Figure 12
Evaporative cooling strategies: Public courtyard. Seville, Spain. The streets and passages of the city combine courtyards, gardens, and a landscape rich with planting and water fountains (Photo: Helen Kessler)

H4 – To recover the heat that rises by natural convection to the top of the atrium, place a return air duct high in the space, possibly augmenting its temperature by placing it directly in the sun. Heat recovery can be accomplished if the warm air is redistributed either to the lower area of the atrium (a ceiling fan) or redirected (and cleaned) to the mechanical system, or through a heat exchanger if the air must be exhausted for health and air-quality reasons.

Because a large air volume must be heated, an atrium is not an efficient solar collector per se. But the high volume helps to make an overheated space acceptable, especially if the warmest air rises to the top. If the atrium is surrounded by buildings on all sides, direct winter sun is difficult if not impossible to capture except at the top of the skylight enclosure. However, by facing a large skylight and/or window opening toward the equator, direct winter solar heating becomes entirely feasible.

In cool climates, an atrium used as a solar heat collector would require as much winter sunlight as possible. In overbright conditions, dark finishes on surfaces where the sun strikes will help reduce glare and also to store heat. On surfaces not in the direct sun, light finishes may be best to reflect light, especially

Bioclimatic Design. Table 3 Extract from consumer survey of 84 solar homes (Watson [14])

Perceived problems	% able to correct	% not able to correct
Glare	14	02
Excessive humidity	12	01
Condensation on windows	10	11
Keeping glass clean	26	07
Stagnant odors	10	00
Fading of furniture, walls, coverings	05	10
Lack of privacy	11	05
Drafts	07	04
Rooms cool down too fast	12	06
Not warm enough	07	02
Extreme temperature swings	10	06
Weather stripping or caulking maintenance	10	00
Covering sloped windows/ skylights	05	04
Assured solar access	00	01
Zoning restriction (solar panels)	00	01
Building code restrictions (retrofit)	01	01
Mechanical/electrical failures	02	00
Overall satisfaction with program	98	02

welcomed under cloudy conditions. In most locations and uses, glass should be completely shaded from the summer sun. Although not practical for large atriums, in some applications greenhouse-type movable insulation might be considered to reduce nighttime heat loss.

Natural Cooling

Several guidelines related to the use of an atrium design as an intermediary or buffer zone apply to both heating and cooling. If an unconditioned atrium is located in a building interior, the heat loss is from the warmer surrounding spaces into the atrium. In buildings with large internal gains due to occupants, lighting, and machines, the atrium may require cooling throughout the year. If one were to design exclusively for cooling, the following principles would predominate:

C1 – To minimize solar gain, provide shade for the summer sun. According to the particular building use, the local climate and the resulting balance point (the outside temperature below which heating is required); the "overheated" season when sun shading is needed may extend well into the autumn months. While fixed shading devices suffice for much of the summer period, movable shading is the only exact means by which to match the seasonal shading requirements at all times. In buildings in warm climates, sun shading may be needed throughout the year.

C2 – To use the atrium as an exhaust air plenum in the mechanical system of the building. The great advantage is one of economy, but heat recovery options (discussed above) and ventilation become most effective when the natural airflow in the atrium is in the same direction and integrated with the mechanical system.

C3 – To facilitate natural ventilation, create a vertical "chimney" effect by placing ventilating outlets high (preferably in the free-flow air stream well above the roof) and by providing cool "replacement air" inlets at the atrium bottom, with attention that the air stream is clean, that is, free of car exhaust or other pollutants.

The inlet air steam can be cooled naturally, such as accessed from a shaded area. In hot, dry climates, passing the inlet air over water such as an aerated fountain or landscape area is particularly effective to create evaporative cooling. Allowing the atrium to cool by ventilation at night is effective in climates where summer nighttime temperatures are lower than daytime (greater than 15°F difference), in which case the cooling effect can be carried into the next day by materials such as masonry (although, as a rule, if the average daily temperature is above 78°F (25.5°C), thermally massive materials are disadvantageous in non-air-conditioned spaces because they do not cool as rapidly as a thermally light structure). The microclimatic dynamic is no different than that evident in the Indian tepee – when stack ventilation is possible through a roof aperture, the space will ventilate naturally even in the absence of outside breezes, by the driving force of heated air. If air-conditioning of the atrium is needed but can be restricted to the lower area of the space, it can be done reasonably; cold air, being heavier, will pool at the bottom.

While there is apparent conflict between the heating design principle to maximize solar gain and the cooling design principle to minimize it, the sun does cooperate by its change in its apparent solar position with respect to the building. There are, however, design choices to be balanced between the requirements for sun shading and those for daylighting. The ideal location for a sun shading screen is on the outside of the glazing, where it can be wind-cooled. When the outside air ranges about 80°F (26.7°C), glass areas – even if shaded – admit undesired heat gain by conduction. In truly warm climates, a minimum of glazed aperture should be used to prevent undesired heat gain, in which case the small amount of glazing should be placed where it is most effective for daylighting. Heat-absorbent or heat-reflective glass, the common solution to reduce solar heat gain, also reduces the illumination level and, if facing the equator, it also reduces desirable winter heat gain.

In temperate-to-cool climates, heat gain through a skylight can be tolerated if the space is high, so that heat builds up well above the occupancy zone and there is good ventilation. In hot climates, an atrium will perform better as an unconditioned space if it is a shaded but otherwise open courtyard.

Daylighting

In all climates, an atrium can be used for daylighting. Electric lighting cost savings can be achieved, but only if the daylighting system works, that is, if it replaces the use of artificial lighting. (Many daylit buildings end up with the electric lights in full use regardless of lighting levels needed.) Atriums serve a particularly useful function in daylighting design for an entire building by balancing light levels – thus reducing brightness ratios – across the interior floors of a building. If, for example, an open office floor has a window wall on only one side, typically more electric lighting is required than would be required without natural lighting to reduce the brightness ratio. An atrium light court at the building interior could provide such balanced "two source" lighting. An atrium designed as a "lighting fixture" that reflects, directs, or diffuses sunlight can be one of the most pleasing means of controlling light.

The following principles apply to atrium design for daylighting:

L1 – To maximize daylight, an atrium cross-section should be stepped open to the entire sky-dome in predominantly cloudy areas. In predominantly sunny sites, atrium geometry can by based upon heating and/or cooling solar orientation principles.

L2 – To maximize light, window or skylight apertures should be designed for the predominant sky condition. If the predominant sky condition is cloudy and maximum daylight is required (as in a northern climate winter garden), consider clear glazing oriented to the entire sky-dome, with movable sun controls for sunny conditions. If the predominant sky condition is sunny, orient the glazing according to heating and/or cooling design requirements.

L3 – Provide sun-and-glare control by geometry of aperture, surface treatment, color, and adjustable shades or curtains. Designing for daylighting involves compromise to meet widely varying sky conditions. What works in bright sunny conditions will not be adequate for cloudy conditions. An opaque overhang or louver, for example, may create particularly somber shadowing on a cloudy day. Light is already made diffuse by a cloudy sky, falling nearly equally from all directions; the sides of the atrium thus cast gray shadows on all sides. For predominantly cloudy conditions, a clear skylight is the right choice. Bright haze will nonetheless cause intolerable glare at least to a view upward. Under sunny conditions, the same skylight is the least satisfactory choice because of overlighting and overheating. The designer's choice is to compromise. Unless the local climate is truly cloudy and the atrium requires high levels of illumination, partial skylighting can achieve a balance of natural lighting, heating, and cooling. Partial skylighting (i.e., a skylight design that occupies only a portion of the roof surface) offers the further advantage of controlling glare and sunlight by providing reflective and shady surfaces to the view, such as by the coffers of the skylights. Because it is reduced in light intensity and contrast, a surface illuminated by reflected light is far more acceptable to the human eye than a direct view of a bright window area. Movable shades for glare and sun control provide a further means of balancing for the variety of conditions. This can be provided simply by operable canvas or fiberglass shades.

The design principles for heating, cooling, and daylighting can be applied according to building type and local climate. In the northern climates, particularly for residential units or apartments that might be grouped around an atrium, the solar heating potential predominates, while the natural cooling potential predominates in the southern United States. In commercial and institutional structures, natural cooling and daylighting are both important. In this case, the local climate would determine the relative importance of openness achieved with large and clear skylighting (most appropriate for cloudy temperate-to-cool regions) or of closed and shaded skylighting (most appropriate for sunny warm regions). While no single recommendation fits any one climate, the relative importance of each of the design principles is keyed to different climatic regions in Fig. 13.

Garden Atriums

Plants have an important role in buffer zones. If the requirements of plants are understood, healthy greenery can be incorporated into atrium design and contribute to human comfort, amenity, and energy conservation. Plants, however, when uncomfortable, cannot move. Major planting losses have been reported in gardened atriums because the bioclimatic requirements were not achieved. A greenhouse for year-round crop or plant production is intended to create spring-summer or the growing-period climate throughout the year. A winter garden replicates spring-summer conditions for plant growth in wintertime by maximizing winter daylight exposure and by solar heating. Plants need ample light but not excessive heat. Although it varies according to plant species, as a general rule planting areas require full overhead skylighting (essentially to simulate their indigenous growing condition). Most plants are overheated if their roots range above 65°F (18.3°C). Their growth slows when the root temperature drops below 45°F (7.2°C). As a result, a greenhouse has the general problem of overheating (as well as overlighting) during any sunny day and of underlighting (in intensity and duration) during any cloudy winter day.

If the function of the atrium includes plant propagation or horticultural exhibit (replicating the indigenous climate in which the display plants flower), then clear-glass skylighting is needed for the cloudy days and adjustable shading and overheating controls are needed for sunny days. If the plant beds are heated directly, by water piping, for example, then root temperatures can be maintained in the optimum range without heating the air. As a result, the air temperature in the atrium can be cool for people, in the 50°F (10°C) range, with the resulting advantage of providing a defense against superheating the space. People can be comfortable in lower air temperatures if exposed to the radiant warmth of the sun and/or if the radiant temperature of surrounding surfaces is correspondingly higher, that is, ranging above 80°F (26.7°C). Lower atrium temperature offers a further advantage to plants and energy-efficient space operation because evaporation from plants is slowed, saving water and energy (1,000 Btu are removed from the sensible heat of the space with each pound of water that evaporates). Air movement aids plant growth, if gentle and pervasive. Air circulation reduces excessive moisture buildup at the plant leaf and circulates CO_2, needed during the daytime growth cycle. The requirements for healthy planting and indoor gardening can thus be combined with energy-efficient atrium design for benefit of both plants and people (Fig. 14).

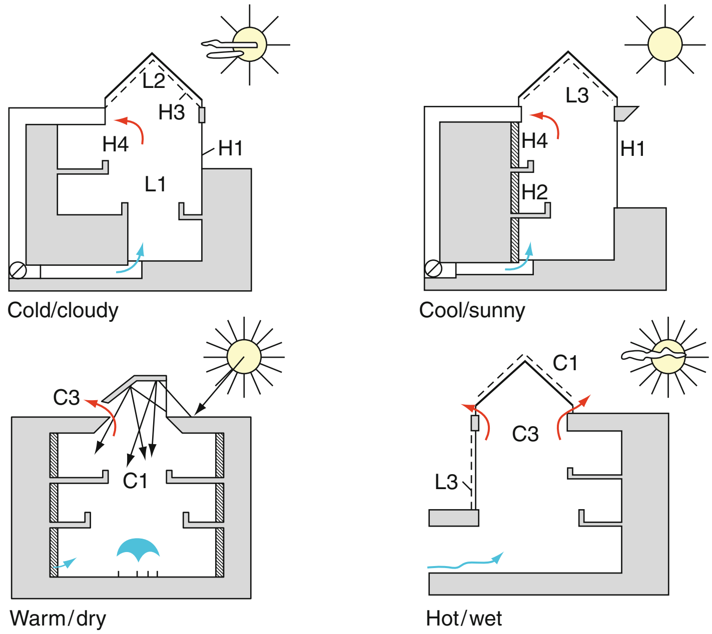
Large-Scale Applications

Bioclimatic design principles and practices are not limited to small-scale buildings alone. The physical basis of passive heating and cooling dynamics are somewhat constrained to near-envelope zones, subject to dimension of spaces in and around the building perimeter. However, these can and should be integrated with larger scale mechanical strategies of air movement, preheating, and ventilation.

Daylighting techniques are scalable and can be applied to exterior envelope, skylighting, and atrium (light shaft) options. The history of buildings from the nineteenth century indicates possibilities, while improved glazing, shading, and insulation increase options for natural lighting that apply to large buildings.

Figure 15 diagrams the site and building opportunities for energy collection, storage, and distribution that may be integrated as combined passive and active means of bioclimatic design.

Several publications document 1980s' and 1990s' applications of passive solar, daylighting, and related bioclimatic elements in larger-scale buildings. Burt Hill



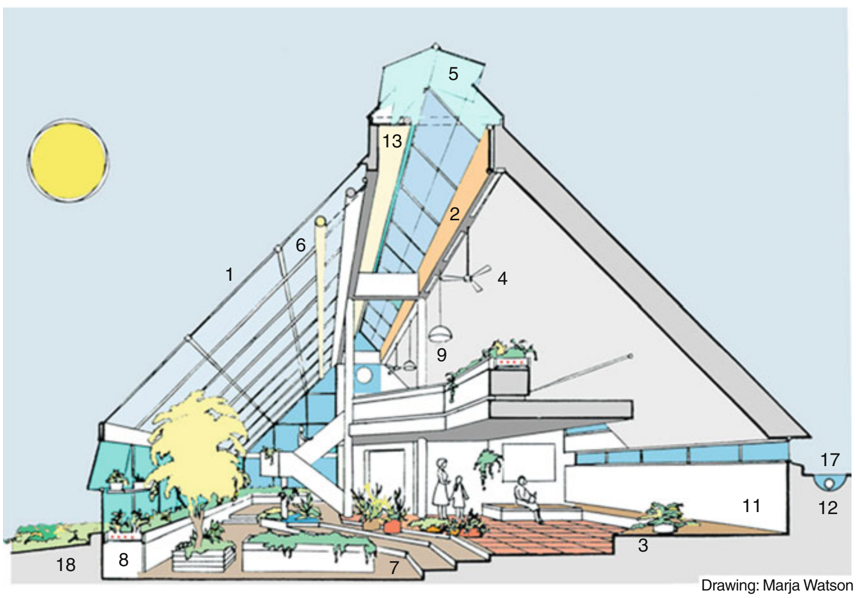
	Cold/cloudy Seatitle Chicago Minneapols	Cool/sunny Denver St. Louis Boston	Warm/dry LosAngeles Phoenix Midland TX	Hot/wet Houston New Orieans Miami
Heating				
H1 To maximize winter solar heat gain, orient the atrium aperture to the south.	●	■	▼	
H2 For radient heat storage and distribution, place interior masonry directly in the path of the winter sun.	▼	■	●	
H3 To prevent excessive nighttime heat loss, consider an insulating system for the glazing.	●	■		
H4 To recover heat, place a return air duct high in the space, directly in the sun	■	●	▼	
Cooling				
C1 To minimize solar gain, provide shade from the summer sun.		■	■	●
C2 Use the atrium as an air plenum in the mechanical system of the building.	■	■	■	■
C3 To faciliate natural ventilation, create a vertical “chimney” effect with high outlets and low inlets.	■	■	■	●
Lighting				
L1 To maximize daylight, use a stopped section (in predominantly cloudy areas).	■	▼		
L2 To maximize daylight, select skylight glazing for predominant sky condition (clear and horizontal in predominantly cloudy areas).	■	■	■	■
L3 Provide sun- and glare-control	■	■	●	■

Key: ● – Very important; ■ – positive benefit; ▼ – discretionary

Bioclimatic Design. Figure 13

Appropriateness of bioclimatic principles for atrium design. The diagrams provide guidelines for the design of atria and lightcourts in various climates. Watson [15]

a



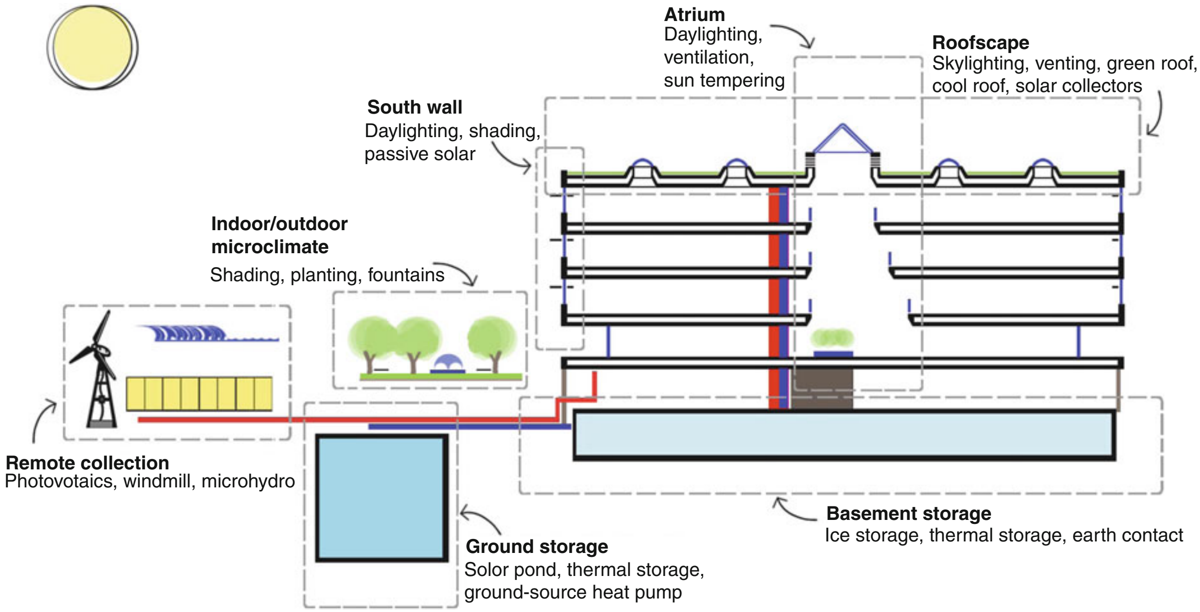
Energy design techniques

1 South-facing greenhouse
2 Solar collectors
3 Thermal storage elements
4 Ceiling fans
5 Roof monitor
6 Operable sun-shade
7 Earth-contact floor
8 Root-bed heating
9 Grow-lights
10 Composting bins
11 Wood stove w/ heat recovery
12 Well-insulated structure
13 Operable insulating curtain
14 Automatic temperature controls
15 Energy-efficient lighting
16 Water-saving plumbing
17 Roof-water collection
18 Earth-berms

Design goals
Helps plants to grow
Uses solar heating (winter)
Uses natural cooling (summer)
Uses natural lighting
Saves non-renewable resources

b

Bioclimatic Design. Figure 14
(**a**) Solar greenhouse and wintergarden. Nature Center, New Canaan, CT USA. Donald Watson, FAIA and Buchanan Associates, Architects. 1984 (Photo: Robert Perron). (**b**) *Cross-section New Canaan Nature Center Greenhouse.*
A broad range of energy conserving and bioclimatic design features are integrated in the design (Illustration: Marja Watson)



Bioclimatic Design. Figure 15
Large building opportunities for microclimatic design integration. Bioclimatic design extends to a larger scale and provides lower demand for integrated heating, cooling, and lighting systems (Watson [16])

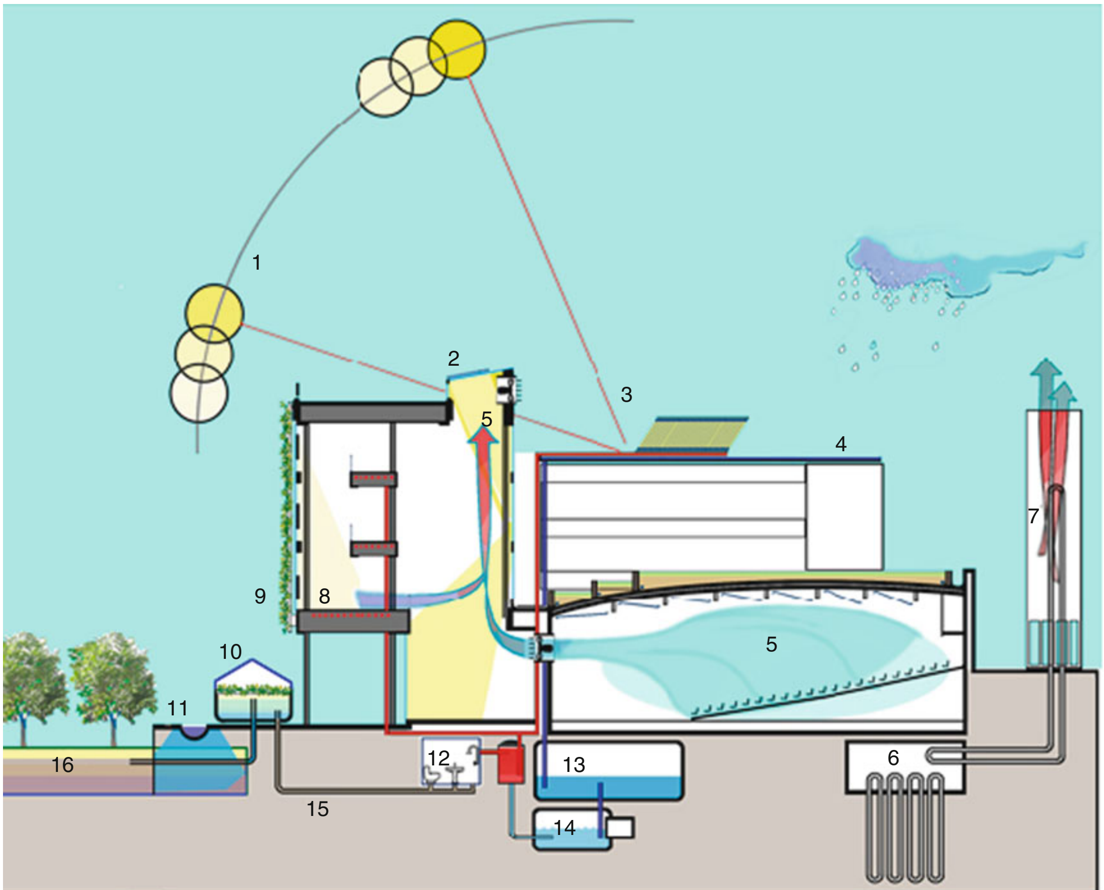
Kosar Rittelmann/Min Kantrowitz Associates [17], provides a summary report, including several years of performance data, post-occupancy evaluation, and user surveys of 20 medium- to large-scale buildings assisted by the US Department of Energy Passive Solar Commercial Demonstration Grants. The grant program provided design and research assistance for building owners who had projects underway, but no so far advanced that they could not incorporate significant innovative approaches to energy conservation.

William M.C. Lam [18], provides a detailed discussion of sunlighting large buildings, including performance documentation of case studies and lessons learned. Several related projects involved faculty and students of Schools of Architecture in courses that undertake post-occupancy evaluations of completed buildings, monitoring all building energy, including air quality and daylighting, providing an archive of critical building assessments [19].

A number of current building designs at a large scale provide exemplary applications of microclimatic design integration with heating, cooling, and lighting systems, with additional consideration of water and waste recycling. Such examples set standards for low energy and environmental impact, with relative value based upon building type and climate (Figs. 16 and 17).

Future Directions: Bioclimatic Design at the Urban Scale

Many studies address microclimatic impacts at the urban scale, described as “bioregional design” by the



1 Daylighting and sun tempering
2 Photovoltaic collectors
3 Evacuated tube solar collectors
4 Rainwater harvesting
5 Displacement ventilation
6 Ground source heat pump
7 Heat recovery
8 Radiant heating
9 Deciduous living wall
10 Solar aquatic biofiltration
11 Stormwater to raingardens
12 Solar DHW
13 Rainwater cistern
14 Water purification
15 Grey and blackwater recovery
16 Greenscape irrigation

Bioclimatic Design. Figure 16
Center for interactive research on sustainability (CIRS) University of British Columbia, Vancouver, Canada. Designed as a “living laboratory” for study of building technologies (Busby Perkins+Will, Architects)

Olgyays [2]. Perennial topics have included solar access, evident in early twentieth-century studies related to daylighting and solar access for light and health, as well airflow and ventilation. Urban heat island effects have been addressed by studies of the effect of vegetation and “cool roofs.” The prospect of climate change and extreme weather has, in recent years, added increased concern for design for resilience,

Passive measures	Active measures	Artic	Tundra	Upland	Continental	Temperate	Mediterranean	Subtropical	Tropical	Savannah	Steppe	Desert
Natural ventilation					4	2	2	1	1	1	1	1
	Mechanical ventilation	3	3				4	3	2	2	2	2
Nighttime ventilation						3	2	1	1	1	1	1
	Air conditioning							3	3	3	3	2
Evaporative cooling										3	2	1
Thermal mass			4	4	2	3	2				3	2
Light construction								3	3	2	4	4
	Mechanical heating	1	1	1	1	2	4				4	
Passive solar				2	2	1	2					
Heat of occupancy		2	2	2	3	3	4					
Insulation		1	1	1	1	2	3					4
Solar control shading					4	3	2	2	2	2	1	1
	Electric lighting	2	2	4	4	4						
Daylighting		2	2	2	2	2	2	3	3	3	4	4

Key
1 Highest value
2 High value
3 Good value
4 Some value

Bioclimatic Design. Figure 17
Summary of Bioclimatic/Energy-Efficient Design Measures. The relative value of bioclimatic design strategies depends upon on climatic zone variations (Adapted from Jones cited in UNEP 2007)

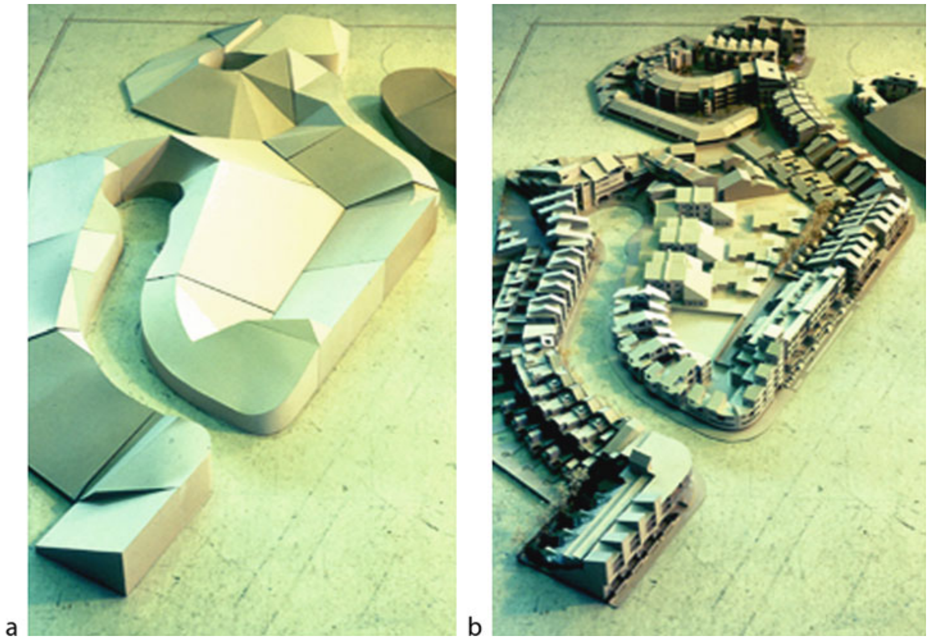
mitigation, and adaptation to extreme weather, including flooding, drought, and increasing global warming. While full discussion of these topics is well beyond the scope of this entry, a few selected references indicate foundation studies and future directions.

Solar Access

Solar geometry. Studies by Ralph Knowles [20] undertaken over several decades with students at the University of Southern California have developed the notion of assuring solar access to buildings, for sun tempering, daylighting, and solar collection. His studies have demonstrated that solar access can be guaranteed in most urban areas while keeping within conventional medium to medium-high density floor to area ratios (FARs) (all but very high rise districts) (Fig. 18).

Bioclimatic Data at the Urban Scale

Baruch Givoni [21] compiles a broad survey of urban bioclimatic data and design applications, with emphasis on measured data, along with



Bioclimatic Design. Figure 18
(**a**) Solar Envelope for a medium density neighborhood of Los Angeles. (**b**) A possible mixed-use community conforming to the solar envelope (Photos courtesy of Ralph L. Knowles)

Bioclimatic Design. Table 4 Average air and surface temperatures measured during a sequence of several clear days in summer (Givoni [21])

Location	Air temperature (°F)	Surface temperature (°F)	Air temperature (°C)	Surface temperature (°C)
Parking lot	79	122	26.1	50.0
Open plaza	78	107	25.6	41.7
Shaded walk	76	80	24.4	26.7
Grass lawn	75	88	23.9	31.1
Behind shrubs	74	73	23.3	22.8

discussions of challenges of data measurement at the urban scale.

Table 4 shows averages of air and surface temperatures measured at a height of 1 m (3.3 ft.) around noontime on the UCLA campus during a sequence of several clear days in summer. The lowest temperatures were in a space between a line of high shrubs and a wall of a building.

Bioclimatic Design. Figure 19
Pocket Park, New York City. Paley Park creates a small area of respite, with a cooling microclimate created by evaporative cooling, shading, and wind protection, while water fountain sound helps neutralize urban clamor (Photo: Donald Watson)

Bioclimatic Design. Figure 20
Wind tunnel. Smoke tracing helps to visualize wind effects of building form at the urban scale (Photo: Donald Watson)

Givoni's research and overview points to opportunities for continued research at the urban scale, supporting an approach to urban planning based on bioclimatic analysis and design (Fig. 19).

Urban Air Quality

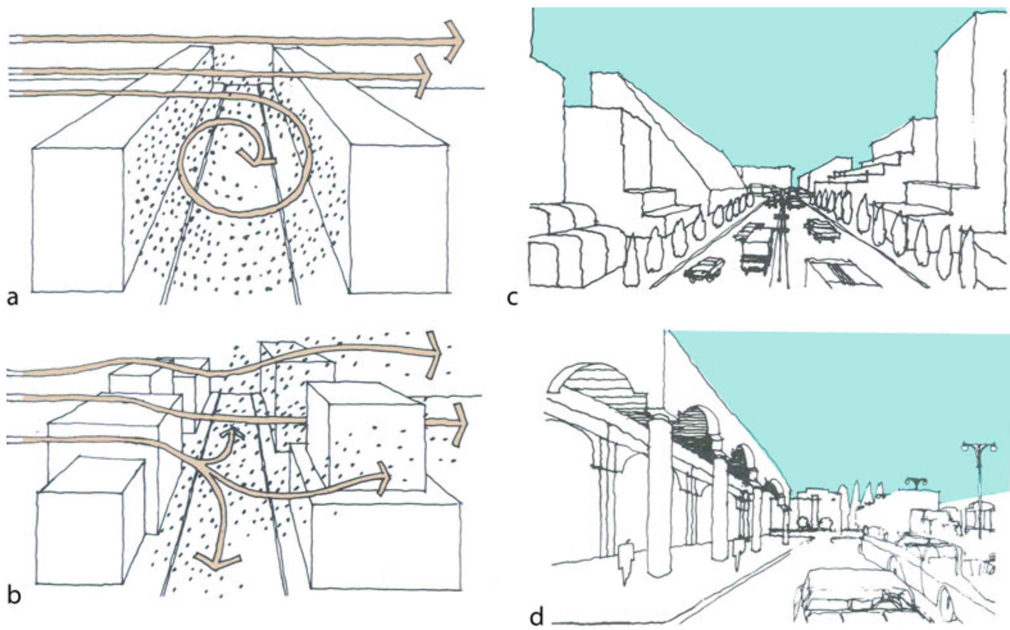
Studies of wind at the urban scale have considered force of winds for structural and exterior envelope design, as well as for wind tunnel (accelerating force of winds at constrained building openings), as well as aerodynamic shapes to induce natural ventilation. Models for such studies have included scaled wind tunnels, flow models, and full-scale mock-ups exposed to simulated wind forces (Fig. 20).

Studies by Anne Whiston Spirn [22] have utilized research on urban wind effects to propose design strategies to reduce pollution in city streets and public ways, principally by opening building forms to less constrained airflow (Figs. 21 and 22).

Resilience to Natural Disaster

Climate change is evident in global warming, extreme weather and storm events, flooding, and drought. The line of influence that climate had upon design is in a sense reversed. Design now influences climate in the way that buildings, infrastructure, cities, along with agricultural and industrial practices have in fact been executed without regard for bioclimatic impacts.

The natural landscape that has evolved in response to climate and water regimes over millennia had adapted to long-evolving patterns of rainfall, aridity,



Bioclimatic Design. Figure 21

Air Quality. The urban designer has opportunity to utilize strategies to improve air quality at the urban microclimatic scale. Anne WS. [22]. (**a**) – Street canyons lined with buildings of a similar height, oriented perpendicular to the wind direction tend to have poor air circulation compared to (**b**). (**b**) –Street canyons lined with buildings of different heights and interspersed with open areas have better air circulation. (**c**) – To promote air circulation in street canyons, step buildings back from the street, increase openings, and vary building heights. (**d**) – To promote air circulation in street side arcades, design them with high canopies and airflow outlets

heat, and cold. Historical flood conditions were accommodated within the watershed ecology and its coevolving plants and animals. When those patterns are disrupted and the natural landscape is altered, flooding risks and disasters increase, as much a result of human actions as natural occurrence.

While the prospect of sea level rise is undefined as to extent and time, the recent incidence of historically unprecedented natural disasters has impelled some nations and regions to undertake programs of adaptation and mitigation. The Netherlands has undertaken a 100-year plan to address flooding by an integrated and phased set of improvements to dykes, removals, and elevations of buildings in increased flood plains, and abandoning the most exposed risk area to natural recovery. In Japan, where spring flooding from mountains has resulted in flash floods in densely populated urban areas that have built up in floodplain areas, the range of actions also include "super-levees," which essentially reconfigure land along river floodplain, while increasing floodable zones that can hold floodwaters during peak floods, while making them available for temporary use at other times, easily evacuated in case of emergency (Fig. 23).

Watson and Adams [23], propose an extension of bioclimatic design to include design for resilience, to adopt precautionary principles in design of buildings, communities, and cities. Resiliency describes the

Bioclimatic Design. Figure 22
Comprehensive plan to improve air quality. Stuttgart, Federal Republic of Germany. Public gardens and open space atop the cities hills and hillside canyons are preserved as vegetated public stairways and watercourses. The hillside canyons funnel cool nighttime airflow to center city streets and downtown parks (Photo courtesy of Dr. Michael Trieb, Urban Planning Institute, University of Stuttgart)

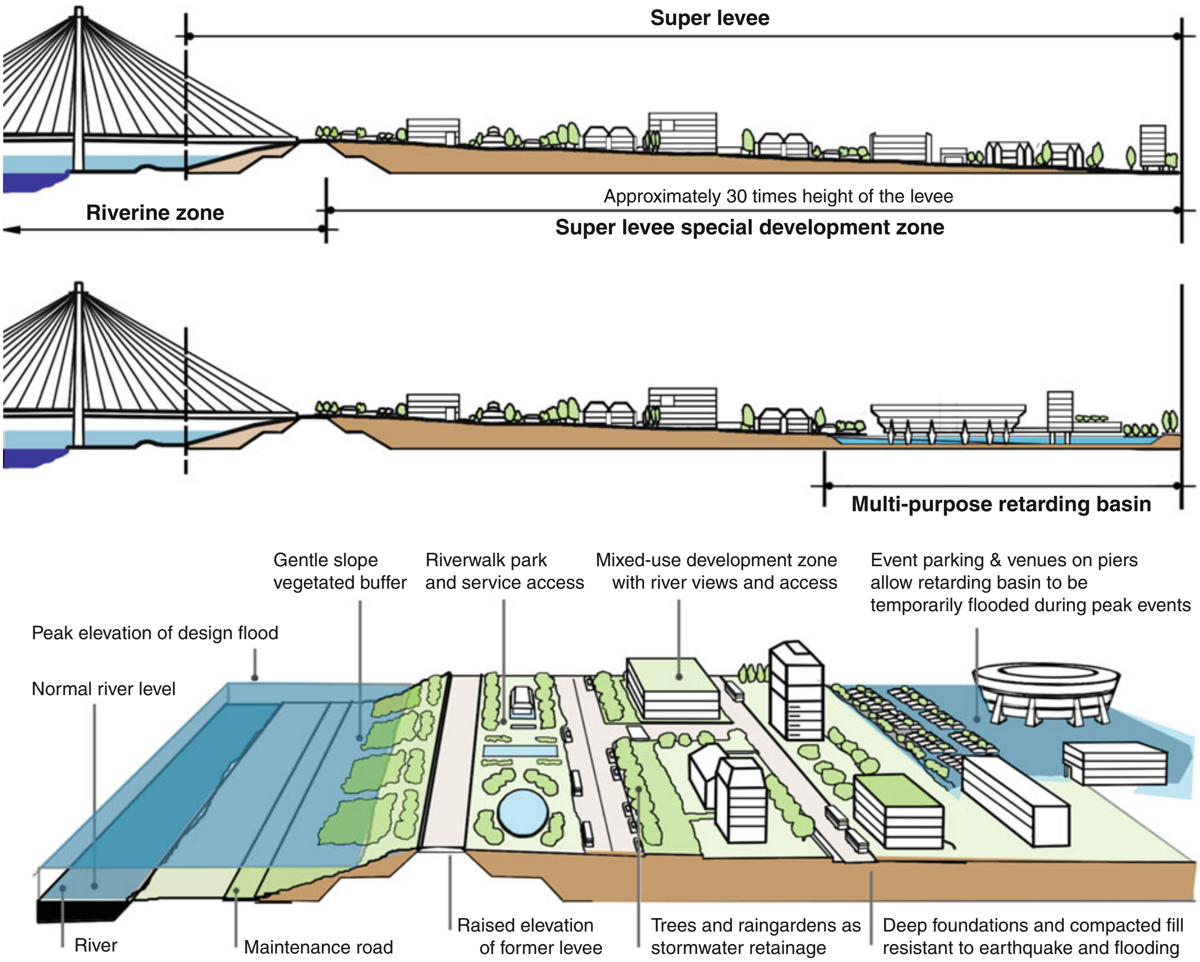
capacity to respond to stress and change of climatic conditions. Resiliency is evident in natural systems in strategies to adjust to variable and extreme conditions. Characteristics of resilient systems include buffering, storage, redundancy, self-reliance, decentralization, diversity, energy conservation, rapid adaptability, and replacement (Table 5).

Summary

Bioclimatic design is based on the analysis of the climate, including ambient energy of sun, wind, temperature, and humidity. Bioclimatic design utilizes passive and ambient energy sources to achieve human comfort through building design and construction, including heating, cooling, and daylighting techniques. Derived from regional and local conditions and opportunities, bioclimatic analysis and design provide both a knowledge base and an inspiration for architecture and sustainable design.

Bioclimatic design analysis is a foundation step in architectural design, essential in the beginning phases to set design guidelines and goals, which can then be compared with actual performance results. By tracking performance results, a designer can thus gain knowledge of the effectiveness of bioclimatic design strategies and techniques for a particular locale and regional microclimates.

A present day challenge is climate change, which portends to increase the severity and period of warming, or overheated, conditions. Climate and weather uncertainty and warming trends should be anticipated in building design to be adaptive by a balance of techniques for heating and for cooling. The challenge to reduce and eliminate where possible



Bioclimatic Design. Figure 23
Super-levees (Japan). Designing infrastructure and buildings for resilience to flooding and extreme weather extends bioclimatic design to new needs and opportunities in regional and urban design (Watson and Adams [23])

Bioclimatic Design. Table 5 Mimicking lessons of nature for resilient design and construction

Principle from nature	Application to resilient design
Absorption	Watershed planning and design (reservoirs, retention ponds, green roofs)
Buffering	Breaks, riparian buffers, rain gardens
Core protection	Zoning, decentralization, self-reliant subsystems
Diffusion	Meanders, wetland and coastal zone landscape, open foundations
Storage capacity	Aquifers, wetlands, reservoirs, cisterns
Redundant circuits	Green infrastructure, wildlife corridors, and multiple service routes
Waste/nutrient recovery	Sustainable stormwater design and waste systems
Rapid response	Smart grid, early warning, emergency responsive systems

the use of fossil fuels for carbon reduction further supports the passive design strategies of bioclimatic design, for its combined advantages of comfort and health, environmental well-being, and resilience to extreme weather.

The enlargement of bioclimatic design to design for resilience is a necessary response to the increased severity of natural disaster. The science of building and urban climatology can fully inform steps to remediate flooding and other risks, so that the natural ecology of regions is returned to its role in moderating extremes and sustaining the diversity of species.

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Biodiversity in Cities, Reconnecting Humans with Nature

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Article Outline

Glossary

Biodiversity The variability among living organisms from all sources, including, "inter alia," terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: This includes diversity within species, between species, and of ecosystems (United Nations – Convention on Biological Diversity).

Connectivity Landscape connectivity is the degree to which the landscape facilitates or impedes movement of plants and animals among habitat patches (cf. [70]).

Corridors and stepping stones Corridors are linear strips of habitat through the landscape of which the length, width, and design are depending on the species. Instead of continuous corridors, for some easy-migrating species (e.g., some bird species) also so-called stepping stones could support their dispersal through the city. A stepping stone connection consists of a subsequent series of small patches of habitat positioned between larger habitat structures [24, 25].

Dispersal Process of individuals leaving the place where they are resident (home) and looking for a new place to live. This behavior can occur both within and between habitat patches [33].

Fragmentation Describes the emergence of discontinuities (fragmentation) in an organism's preferred environment (habitat), causing populations to get isolated from each other, and increased disturbance of remaining habitat. Habitat fragmentation can be caused by geological processes that slowly alter the layout of the physical environment, or by human activity such as land conversion (e.g., natural area that gets "developed" into city area), which can alter the environment much faster and causes extinctions of many species (Wikipedia).

Habitat An ecological or environmental area that is inhabited by a particular species of animal, plant, or other type of organism. For wildlife in cities, this includes the total area used for foraging (e.g., gardens, parks), reproduction, and nesting (this may include buildings, e.g., for bats and some bird species), resting, hibernating, and migrating.

Habitat network An interconnected configuration of habitat patches and corridors.

Habitat patch A relatively homogeneous area that differs from its surroundings. Patches are the basic unit of the landscape that change and fluctuate, a process called patch dynamics. Patches have a definite shape and spatial configuration, and can be described compositionally by internal variables such as number of trees, number of tree species, height of trees, or other similar measurements [25].

Homogenization Biotic homogenization is the process by which the similarity of a biological variable increases across time and space. In the perspective of this chapter, the term "homogenization" is used to describe the increasing similarity of urban wildlife communities (especially "'bird species") in cities across the globe [44].

Landscape ecology The study of how the spatial structure of landscape elements (= different parts of the landscape) affects organism abundance at the landscape level, as well as the behavior and functioning of the landscape as a whole. This includes studying the influence of pattern, or the internal order of

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a landscape, on process, or the continuous operation of functions of organisms [71].

Metapopulation A metapopulation consists of a group of spatially separated populations of the same species which interact at some level. A metapopulation is generally considered to consist of several distinct populations together with areas of suitable habitat which are currently unoccupied (Wikipedia).

Urban wildlife This includes all non-domesticated animals, plants, and other organisms that live in city environments.

Definition of the Subject

Worldwide, the diversity of plant and animal life is diminishing at high speed. At the same moment, more and more humans become city dwellers, with both the proportion and absolute number of people living in cities increasing rapidly. An important link between global biodiversity loss and fast urbanization is the enormous ecological foot print by urban dwellers, the huge demand for natural resources as required by the urban life style. Besides, a generally less well-known impact of the global urbanization of human society is the extinction of wildlife experience. People in cities lack frequent and intense human-nature interactions, as compared to our rural history. This leads to a decreased understanding of and support for plant and animal life. This not only negatively impacts biodiversity conservation efforts; it also restricts the long-term abilities of humans to benefit from nature. By promoting *urban* biodiversity, nature will be enhanced in the direct living and working environment of citizens, enabling humans to reconnect with nature.

This chapter addresses the opportunities to enhance urban biodiversity and its experience by citizens. First we illustrate how the city environment is perceived from a wildlife point of view, which is necessary to recognize opportunities to enhance urban biodiversity. Next, we discuss these opportunities one by one, illustrating with examples how to implement them in practice. We conclude with an exploration of future possibilities to integrate urban biodiversity conservation opportunities in the broader concept of sustainable city planning, design, and management.

Introduction

Why Attention for Urban biodiversity?

The latest global Living Planet Index [79] shows a decline of biodiversity about 30% between 1970 and 2007. This is based on trends in 7,953 populations of 2,544 mammal, bird, reptile, amphibian and fish species. We may therefore conclude that global biodiversity loss is currently happening on an immense scale and rate. This loss of biodiversity not only impacts ecosystem functioning, but also human well-being. The fact is that the world's ecosystems provide a wide range of services (so-called ecosystem services) that are of vital importance for the quality of human life. Degeneration of these services has huge direct or indirect negative consequences for human life: for example, (local) extinction of bees decreases pollination service and consequently food production linked to seed [2].

The urban growth of human society can be considered as one of the main causes of global biodiversity loss. According to the United Nations [73], the level of world urbanization crossed the 50% mark in 2009. In addition, between 2009 and 2050, the world population is expected to increase by 2.3 billion, passing from 6.8 billion to 9.1 billion [72]. At the same time, the population living in urban areas is projected to gain 2.9 billion, passing from 3.4 billion in 2009 to 6.3 billion 2050. Thus, the urban areas of the world are expected to absorb all the population growth expected over the next four decades while at the same time drawing in some of the rural population [73].

The impact of human lifestyle on the natural ecosystem, illustrated by a concept as the ecological footprint, is extremely high for humans living in cities [53]. As example, the city of Vancouver, Canada, requires 180 times more land to generate and process materials than the city actually occupies [52]. Already in the 1970s it was documented that modern cities consume 10–100 times more energy (per unit area) than natural systems [50]. All in all, the urban life style is an important cause of the worldwide decline of ecosystem functioning and biodiversity. It is therefore counterintuitive to think of urban areas as focal areas for biodiversity conservation, however there are several arguments to do so [45]:

1. *Source approach to diminish environmental impact*: As the majority of people is concentrated in urban areas, exploiting conservation efforts in cities (1) will reach many people and (2) any reduction in the huge city's environmental impact will be a positive step toward sustainability.
2. *To reconnect humans with nature*: Most people who live in urban areas are largely disconnected from nature. This means that a worldwide "extinction of (wildlife) experience" is currently taking place. To counteract, the places where people live and work should be designed so as to provide opportunities for meaningful interactions with the natural world. Doing so has the potential not only to engender support for protecting native species, but also to enhance human well-being [48]. Urban wildlife experience has psychological benefits for citizens [26] and may contribute to so-called socio-ecological systems, as such being an important strategy to enhance the resilience of local citizens (see [23]).
3. *To recognize cities as (potential) biodiversity hotspots*: People, plants, and animals share the same preference for areas naturally rich of resources. Urbanization is occurring in numerous (former) biodiversity hotspots worldwide, and has been identified as a primary cause of declines in many threatened and endangered species [49]. Although urbanization processes often have diminished a large part of the original biodiversity richness, the remnant "green space" (according to its management) usually still contains a certain (potential) value for biodiversity conservation. For example, the UK city of Sheffield inhabits a high number of bird species (n = 77), with only three nonnative species [27].

A Different Scope: Approaching the City from a Wildlife Point of View

In natural situations, the appearance and change of landscapes and their attached biodiversity are products of abiotic and biotic processes. Human activities, such as agriculture, modify these relationships. In the urban landscape, the hierarchy of processes is absolutely different: Here, the biodiversity settlement is first depending on human appreciation and management, abiotic and biotic factors play a less important role. So, to better understand how plants and animals may survive in these man-made landscapes, a good understanding of the different actors in the urban environment and the "realities" they perceive is crucial.

Obviously, cities accommodate a range of human actors. Apart from humans as individuals inhabiting in the city (the "residents"), city dwellers employ various activities that makes that they can also be grouped as e.g., students, sportsmen, entrepreneurs, employees, patients, (allotment) gardeners, elderly people, or urban professionals (the latter term referring to those people who professionally deal with city planning, design, and management), etc. Depending on their age, societal status, and individual preferences, citizens may fit in only one or in a whole set of urban actor groups. Moreover, each of these urban actor groups, including residents, has its own favorite part of the city. They also have each their own demands concerning what the city should deliver: Residents like nice and safe residential neighborhoods; sportsmen and - women like good and sufficient sport accommodations; etc. This makes that city planning and design can be a complex process, as there usually are many urban stakeholders to be involved.

Some of the "actors" in cities are nonhuman, being plants and animals. Most species are considered as real "wildlife" because they survive in the city on their own; others are domesticated and (partly) depend on care by humans (pets and cultivated garden plants). For all of them, cities provide them with different needs, in essence similar as for humans, being "habitats" where they can live, eat, reproduce, move, and communicate with others. However, wildlife generally has specific habitat requirements that are generally different than those of humans. For example, most birds prefer trees and shrub as nesting place above buildings (although there are exceptions as swifts and house sparrows).

To understand what the city is like as wildlife habitat, humans should project themselves in the plants and animals that inhabit city environments. This is because wildlife often evaluate the reality of the city in a different way than people would do. Three different realities of the city can be perceived by human and nonhuman urban actors:

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 1
The Garden snail *Cornu/Helix aspersum* is a cosmopolitan species, originating from the south of Europe (Mediterranean). Buildings and surrounding green (*biophysical reality*) are considered by the snail as part of its urban habitat (*functional reality*), meanwhile humans designate these housing areas as living areas for themselves (*planning and design reality*). The coexistence of humans and these snails in residential areas leads to positive and negative interactions: the garden snail is seen as a pest for garden flowers, but also inspires people through its appearance and behavior, and acts as food for e.g., birds (which are preferred urban wildlife by residents). Photo: Robbert Snep

- *Biophysical reality*: The reality of what is physically there: buildings, roads, vegetation, bare soil, open water. Geographers use to describe the physical reality ("land cover"), these days more and more supported by satellite and aerial photo images. Urban actors (both human and wildlife) perceive the biophysical reality as (one of) the realities they have to deal with.
- *Functional reality*: The reality of how the city is actually *used* by different urban actors. In their use of the city, human actors thereby take the biophysical reality (what's there?), the functional reality (how the city is being used by themselves and others), and the planning and design reality (what is it meant to be?) in consideration. Wildlife only look to the biophysical and functional reality, the latter including the human and wildlife use. Obviously, wildlife does not take the planning and design reality into account, as they are unaware of city plans.
- *Planning and design reality*: This reality has to do what a specific part of the city officially is designated as, or what it meant to be for. The planning reality is predominantly shaped by urban professionals in planning and design (architects, landscape architects, urban planners, regional and landscape planners etc.), and subsequently assigned in municipal, regional, federal or national plans and documents, and as such taken in consideration by human actors.

Figure 1 presents an example that illustrates the differences between the realities, and why it is important to be aware of the differences among the realities and the way they are perceived by humans and wildlife in the city.

City Environments as Wildlife Habitat

Cities as Landscape

Although most people would only associate rural and natural environments with the term "landscape", city environments can also be considered as real landscapes (e.g., [12]). This is because due to their size (usually >100 km^2) they act on a landscape level, and because of their distinctive land use pattern they sharply contrast from their rural or natural surroundings. From a wildlife point of view the features of the urban landscape determine its habitat suitability and availability.

As the urban landscape largely consist of buildings and paved area, its stony and built-up character make that they resemble rocky and cliff landscapes. Sky scrapers thereby act as mountain cliffs, whereas the streets between high-rise buildings (e.g., in Manhattan, New York) act as canyons. For species as the Peregrine falcon (*Falco peregrinus*), these high-rise city environments have become a secondary habitat, next to their natural cliff habitat.

Cities also appear to be different in terms of climate, as compared with the often more vegetated surrounding landscapes such as forests, swamps, mountains, or agricultural land. Because of their stone surface (and lack of the evaporation possibilities that vegetation has), cities warm up faster, effectively retain the heat, and throw it out during the night. In addition, exhaustion gases (traffic and industry) and the heating of buildings add up to an increased temperature, especially during nights. The main reason for the nighttime warming, however, is that buildings prevent surface heat from radiating into the relatively cold night sky. As a result, city night temperatures surpass the average regional temperature with several degrees. During days there is also a, yet smaller, difference in temperature. This "being warmer than the rural surroundings" phenomenon is called the UHI (*urban heat island*) effect (e.g., [69]). The UHI effect causes health problems for humans during the summer (as it contributes to extreme heat, which causes high mortality rates), but also affects wildlife in different ways. For example, in temperate climates (sub)tropical plant and animal species are more likely to survive in city environments than in the natural or rural surroundings of the city. In Northwest Europe, plant species as Common Fig (*Ficus carica*) and Olive (Olea *europaea*) from the much warmer Mediterranean region can survive in sheltered spots within cities, but would die in the rural surroundings of these cities during winters. The same process is observed on small Mediterranean ferns in France [18] showing that cities therefore present an interesting preview on how global warming may support the invasion of thermophilic species into currently colder regions.

There are more features that distinguish urban landscapes from natural and rural environments. One of them is air quality. Because of traffic and industrial gasses, the quality of city air is often worse than in the rural surroundings. The air pollution directly limits the habitat suitability of cities for e.g., most lichen species but also impacts the survival rates of urban plants and animals in general [6].

Cities are places with an excess of noise. Car traffic is a main cause of city noise, thereby making it difficult for some animal species to communicate. For example, for territorial birds it is hard to make themselves heard through the traffic noise and as such to defend their territories [54]. Recent studies have shown that bird species may adapt to the noisy city environment. Urban Coal tits (*Parus major*) sing at a higher pitch than their rural congeners, to compensate for the city background noise [61]. From other birds it is known that urban individuals start to sing earlier in the morning than usual for these species, to avoid the noise of the city's rush hour.

Cities are constructed in a variety of places, neglecting whether the physical conditions of the original soil may support the construction of buildings. Some cities are developed in (coastal) wetland regions or in peat soil areas, locations that are not well-equipped for construction buildings. To compensate for this, urban developers make their development sites "construction ready" by removing the original upper soil layer and adding construction-supportive sand layers. In most cities this urban development process has been happening for ages, making that urban soils are highly heterogeneous, with many different soil compositions within a small area. In addition, pedogenesis (the formation of soils) is disturbed by the actual urban land use. As large parts of the city consists of buildings and roads, these parts are sealed and thus isolated from normal interaction with rain and surface water, plant life, sun heat, etc. Also, because of the weight of buildings and heavy car traffic, the soils are compressed, decreasing their permeability for water and soil organisms. On top of this, a portion of the pollution and eutrophication coming from industry

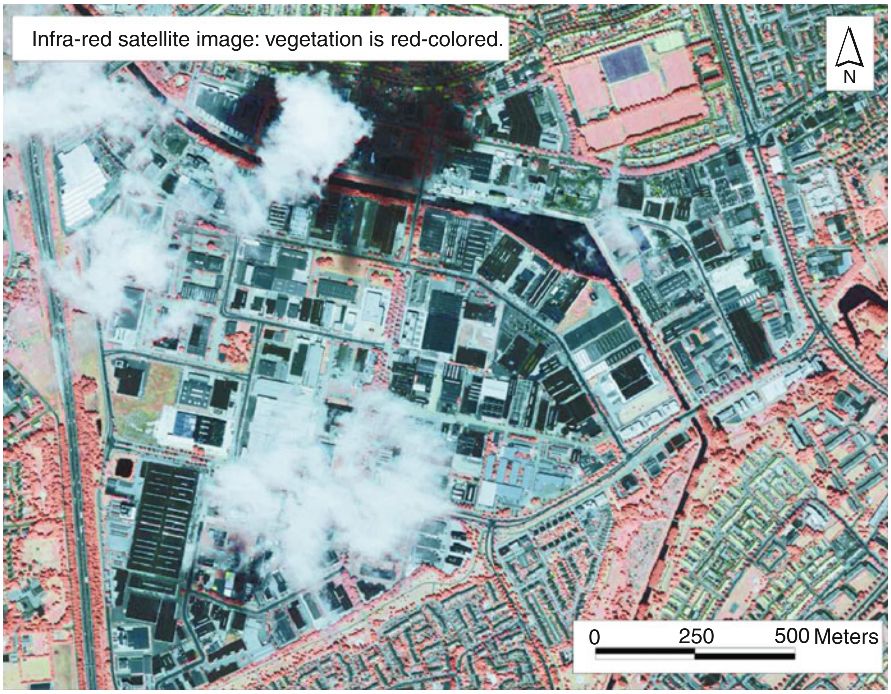
Biodiversity in Cities, Reconnecting Humans with Nature. Figure 2
The Natterjack toad (*Bufo calamita*) is a pioneer species of early successional habitats, including urban fringes. *Left*: tadpoles (black) of this toad species in a small temporary water body at a development location. *Right*: the male toad calling during mate season (Photo: Robbert Snep)

and traffic will find its way to the urban soil. As an example, urban soils often appeared to contain much higher levels of heavy metals such as lead than its rural surroundings [19]. All in all, urban soils are quite different than rural and natural soils, more contaminated and eutrophicated, as soil profiles less developed (because of a disturbed pedogenesis), spatially more heterogeneous and – with all this – thereby in general impacting the habitat quality of cities for plant and animal life in a negative way. An exception would be that, because "to be" urban development sites are usually covered with sand, these young sandy soils provide a – often temporary – habitat for plant and animal species from early successional vegetation [64]. These pioneer habitats enrich the species composition of the city's biodiversity (Fig. 2).

The cycle of water (from clouds, precipitation, surface or groundwater back to clouds via evaporation) is essential for life on earth. On a landscape level, there are huge variations in the amount of water in each part of the cycle, as the cycle of water is taking place on a continental or even global level. In the vegetated parts of the world, being the areas where most human activities occur, human land use has disturbed the water cycle process. In agricultural areas, the surface and ground water flows are highly manipulated to optimize crop yield. In urban areas, this manipulation of water has taken a much more far-reaching level. Surface water is largely canalized, with stony and steep embankments. Sewer systems catch most of the water that precipitates on buildings and streets. In cities with naturally high groundwater levels (like former wetlands), groundwater is sometimes drained or leveled in another way. The evaporation process in city areas is, due to the lack of vegetation, rather poor. In addition, urban water is contaminated by (former) industrial and household waste and by traffic, especially in cities where sewer systems do not function optimally. All in all, water is strongly manipulated in city environments. As water is a vital element for plant and animal life, the deviant quantity and quality of urban water restricts the habitat quality and availability for wildlife in cities.

Cities as Mosaic of Biotopes

Although city landscapes are quite different than rural and natural landscapes, they are all but homogeneous. City landscapes are in fact composed of a wide variety



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 3
Illustration of spatial distribution and portion of vegetation in different urban land use types: sporting fields (*right top*), residential areas (*right bottom*), infrastructure (*left*) and industrial sites (*center*). IKONOS satellite image (Photo: Robbert Snep)

of urban land use types, ranging from residential areas, business districts, shopping malls, and (rail)road structures to urban parks, sport field complexes, allotment gardens, and cemeteries. Within each of these land use types, the actual land cover or soil occupation may also vary quite largely. The spatial heterogeneity is what makes the city that there is not such thing as "the urban biotope" (Fig. 3). Cities are mosaics of biotopes.

For long, ecologists have undervalued city environments in terms of species richness and composition. Most ecologists thought (and many of them still think) that cities would not accommodate a diversity of plant and animal life worth to study. A pioneer in the scientific field of urban ecology, Prof. Herbert Sükopp, provided the counterintuitive insight that cities are rich of species and numerous interesting ecological patterns and processes can be found here. In the 1960s, in the middle of the Cold War between the West and the Soviet Union, he was positioned at a university in West Berlin (Germany). By that time, West Berlin was governed by the West, but the surrounding area controlled by the Soviet Union. Normally, academic ecologists would leave the city and do their field work in rural and natural areas. This was not possible in the case of West Berlin. Herbert Sükopp therefore decided to conduct his ecological field research within the urban area of West Berlin, a unique approach. By mapping the plant communities and biotopes of residential areas, shunting yards, and derelict industrial areas in the city in a systematic way, he discovered that urban environments have a much higher flora and plant community richness than expected. From further studies conducted in German cities, it was later also demonstrated that especially the transition zone from city to rural surroundings is species rich, and that the flora richness of cities can even be higher than the actual surrounding rural land [37]. This latter is due to two facts: (1) the heterogeneity and biotope richness of urban areas and (2) the low flora richness of the intensively managed agricultural regions in

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 4
Bird monitoring in urban environments is not only conducted in backyards and urban parks, but also at industrial sites. At this photo ecologist Martin Melchers is observing urban gulls nesting at the roof of storage tanks in the Port of Amsterdam (NL) (Photo: Robbert Snep)

which many (German) cities are located. Modern operational management methods of farms focus on optimal yield for agricultural products, and include reshaping of the landscape (stripping off hedgerows, ponds etc.) for this purpose. Many of the species of traditional agricultural landscapes have disappeared in the modern agricultural "deserts" due to lack of habitat; some of them find a new habitat in the small-scaled structure of the city edge. As an example, Sálek et al. [55] described a case in which the Grey Partridge (*Perdix perdix*) has colonized derelict parcels in business districts and industrial land located at the city edge.

Urban biotopes can be classified in different ways. Based upon the three realities (biophysical, functional and planning and design reality, see section "A Different Scope: Approaching the City from a Wildlife Point of View"), each classification having its pros and cons. With the *biophysical or land cover* approach, good insights in the abiotic conditions are provided, enabling ecologists where potential habitat for wildlife could be found. For this purpose aerial or satellite images supply with basic information on where vegetation and other habitat characteristics are located (using e.g., infrared sensing techniques), but additional field work is required to detail the land cover of urban areas. With the *functional* approach, the actual use of the urban area by wildlife and humans is mapped. Wildlife can be monitored with a variety of techniques, of which bird counting techniques (e.g., by mapping territories) are probably most well known (Fig. 4). With these monitoring techniques, a good overview of the current habitat value of the urban area for wildlife species can be acquired. With additional inventories on the human use (recreation, traffic) of the urban area, possible causes for differences between apparently similar plots can be demonstrated. In Madrid (Spain) a study to the foraging behavior of Blackbirds (*Turdus merula*) in several urban parks showed that in parks frequently visited by people, the Blackbird behavior and density was different then in similar parks with a lower frequency of visitors [21]. Blackbirds in the more crowded parks spent more time being vigilant and moving away from people and less time searching for food (decreasing food intake). The number of pedestrians was positively correlated with Blackbird distance to pathways and negatively correlated with distance to protective cover. The number of active birds decreased with increase in the number of pedestrians during the day. Blackbird density was negatively related to the number of visitors per park. This study confirmed that human disturbance negatively affects Blackbird feeding strategies in urban parks, ultimately modifying spatial and temporal patterns of habitat selection and abundance [21]. This study also shows that land cover and land use destination alone (in this case "urban park") can be insufficient to determine the habitat value of urban biotopes for wildlife. The actual use of the biotope by others (humans, dogs) appears to have a – though rather invisible – impact. To implement urban ecological knowledge into the design, management, and use of the city (see "planning and design reality"), one should be able to link an urban biotope classification to the design and management jargon and concepts of the city's public space, residential areas, business districts, etc. As there is much variety in habitat quality and quantity within each of the official urban land use types (as assigned in zoning plans), the official land use legend of the city is often not well-equipped for mapping ecological knowledge, so translation between these two different classifications can be difficult.

Fragmentation and Connectivity of (Urban) Habitat

From the 1970s on, ecologists have linked the spatially explicit availability and connectivity of habitat at the landscape scale with the abundance of species at the local scale. Ecological theories as the island biogeography [42] and the metapopulation theory [39, 51] explain how local plant and animal populations are depending of surrounding populations for their long-term persistence. The first publications about these theories mark the start of the scientific discipline of "landscape ecology."

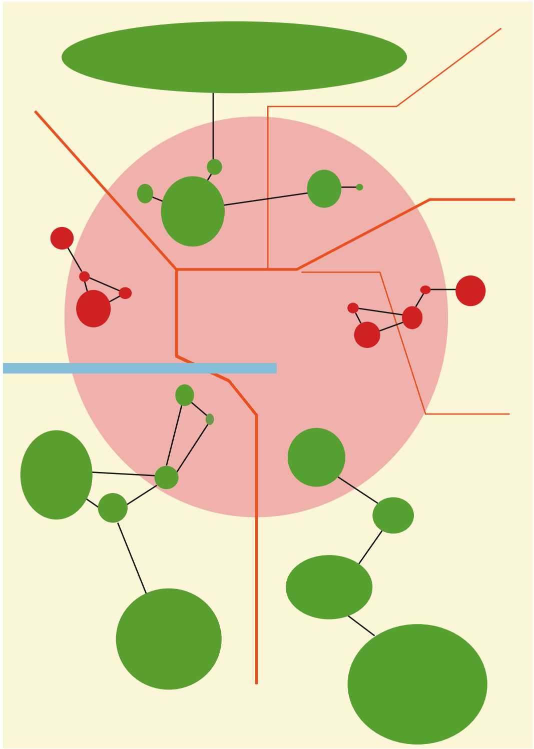
The island biogeography originates from comparative studies on species richness of islands and mainland, thereby illustrating that islands with a larger size and a smaller distance to the mainland are more species rich than small islands that are located far from the mainland. The size of the island thereby is a good predictor of the probability of local population extinction. The smaller the island, the generally less habitat; the smaller the island population, the higher vulnerability for a disaster to impact the whole island population, the higher the extinction rate of the island population. After local extinction, the island may be inhabited again via colonizing individuals deriving from the mainland. The distance to the mainland thereby acts as a good predictor for the colonization probability: the smaller the distance, the larger the chance that the island will be re-colonized. The island biogeography theory can also be applied in situations where there is a very large "source population" (the mainland) and smaller local populations, all located in a larger area of non-habitat.

In the past, habitat used to be much more abundant and interconnected than in current landscapes. In today's human-dominated landscapes habitat is not only reduced in size and quality, but also fragmented by infrastructure and urban development. Here, the island biogeography with its mainland that acts as source area is not applicable, as there often is no enormous mainland habitat. The metapopulation theory is better equipped for these fragmented landscapes.

The metapopulation theory departs from the idea that in fragmented landscapes interconnected local populations may together make up a so-called metapopulation. The long-term persistence of such a metapopulation is achieved by the network setup: (1) local population extinction should be balanced with new colonization from neighboring local populations and (2) the total number of all individuals within the metapopulation should be sufficient. With an extra large local population (a so-called key-population), this total number can be lower than in case all local populations within the metapopulation are small. As the interlinkage between local populations is crucial for the mutual exchange, the habitat pattern at landscape scale determines whether local populations will together function as a metapopulation (Fig. 5).

Several landscape parameters determine the probability that species may survive in the landscape:

- Habitat availability (the amount of habitat available for the species)
- Habitat quality (determines the carrying capacity per area of habitat)
- Habitat connectivity (extent to which habitat patches are mutually connected)
- Individual habitat patch size (determines whether there is a habitat patch in the landscape with sufficient space for a key population)



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 5
Illustration of how networks of local populations (so-called metapopulations) of a ground-dwelling species are distributed in and around a city (*pink*). Road (*orange*) and water (*blue*) infrastructure act as barriers and makes that there are different metapopulations (that instead of one large network). As a result, some metapopulations have sufficient size to overcome environmental fluctuations, and are viable (*green*), others are too small and are nonviable (*red*) (Photo: Robbert Snep)

- Landscape permeability (extent to which the landscape pattern support the migration of species through the landscape, especially the size and character of the portion of nonhabitat is important in this case)
- Barriers (landscape structures that prevent the movement of species through the landscape (e.g., highways for ground-dwelling animals))

Also, some species-specific parameters determine how well the species would be equipped to survive in the landscape:

- Dispersal capacity (extent to which a species is able to migrate through the landscape, e.g., overcome barriers.)
- Dispersal distance (distance that individuals of a species are able to travel to colonize new habitat)
- Home-range size (the size of the area that an animal individual uses during everyday's activities)
- Disturbance sensitivity (level at which a species will be so much disturbed by traffic, recreation, noise, light, etc. in its habitat that this will impact its survival probability)
- Local population size (minimum amount of individuals required to function as local population)
- Key population size (minimum amount of individuals required to function as key population (and thus as an source for neighboring populations) [74])
- MVP size (minimum amount of individuals within the metapopulation necessary for a minimum viable population [59]; for metapopulations with a key population the minimum is lower than without a key population, [74]).

Each landscape is unique, each species is unique; however there are some general rules about how to deal with landscape planning and design, as seen from the viewpoint of biodiversity conservation:

1. Conserve (or re-develop) sufficient habitat area for conservation target species. "Sufficient" should meet habitat criteria for *viable* plant or animal populations [67].
2. Use the SLOSS (Single Large patch Or Several Small patches) principle while targeting (to be) habitat patches for conservation [1, 60]. This is as habitat networks should have sufficient size for a (meta) population size and sufficient connectivity (to support colonization of the patches).
3. To meet criteria for habitat connectivity, make sure that the habitat in the area is optimally interconnected, so species can migrate from one habitat patch to another [58]. In landscape and conservation planning, so-called ecological corridors are often assigned to support plant and animal dispersal [24]. These corridors are linear strips of habitat through the landscape of which the length, width, and design are depending on the species. Instead of continuous corridors, for some easy-migrating species (e.g., some bird species) also

so-called stepping stones could support their dispersal through the city. A stepping stone connection consists of a subsequent series of small patches of habitat positioned between larger habitat structures.

Urban environments are highly fragmented landscapes, in which habitat availability and connectivity is generally insufficient to support the population viability norms of many species. So the application of the previous concept is not so easy. It appears today, after some urban studies on species dispersal and landscape availability to conserve populations, that complementary consideration has to be suggested in these highly fragmented urban landscapes. For example, the SLOSS rule is generally not possible and it seems interesting to promote also small green spaces and diverse kinds of green structures in dense city environments. The goal here is not to construct new large patches of biodiversity when it is not possible, but to permit, at least, both the dispersal of a maximum of species with "stepping stones" and to increase the interface between nature and citizens. After all, increasing the street plantation (street trees, road verges) in an ecological way would promote for several species the dispersal opportunities in towns: from park to park, and between areas of private gardens and business areas.

Another process that is generally forgotten is the impact of the city on the capacity of species dispersion at regional level. Under climatic change, wildlife modifies their biogeographical area of distribution, moving to the north [32]. This adds a justification to the need of a good capacity of continuity in landscape at all the scales, including the urban areas. The town becoming megalopolis with continuous building land use acts as barriers to the species movement and especially to the dispersion to new area (to the north) for all the species that move with difficulty. Given transparency to the town, e.g., permitting the species movement is also a challenge of a sustainable city.

Urban Wildlife Species and Communities

On Eating and Being Eaten

The food resource and/or its quality are an important factor of the settlement of animal in town. The availability of grass for first consumers, insects or gastropods for first predators and small vertebrates for second predators are fundamental both to explain the presence of species in a habitat and to explain the stability of the biodiversity through the quality of the food chain. Obviously the urban areas do not present all the availability of food for each step of the food chain and some kinds of animals are favored. For example, the omnivorous and detritivorous animals, small (snails, flies. . .) as well as large (gulls,corvids, rats. . .) ones, are capable to use the rubbish dumps and all wastage from human activities. These species can become very numerous and create several problems of cohabitation (e.g., [10]). Other species take advantage of the feeding behavior of inhabitant that is important in private as well as public spaces. This typical urban source explains the success of pigeons [30] but also of some exotic species such as parakeets introduced in numerous towns [68]. However, the use of refuse is commonly reported for other species living in urbanized areas, for example, tits [14], blackbirds [57], gulls [7], or mammals such as raccoons [43] or foxes [56].

In general, urban areas appear clearly poor in food resources for specialist species. Wetlands are scarce, so water birds and aquatic fauna are also scares. The absence of old trees that permit settlement (shelter, food) of numerous insects and birds also explain the absence of several communities of animals. However, the town presents more and more vegetation and welcomes more animals today than some decades before. Insectivorous birds seems to decrease in numerous European town in 1970s [28], but today these birds appear to be more numerous with the reduction of car pollution and pesticide use. In the same time, the recent reduction of some garbage sources in numerous countries has also limited the proliferation of some problematic animals (rats, gulls,. . .).

For some generalist birds breeding in towns, a behavioral flexibility exists through diet plasticity, for example the Herring Gull [7], while for other generalists, such as the starling, it is less clear. Starlings can modify their diet composition in winter [20], but its diet variability in towns during the breeding period seems to be limited [46]. However, successful generalists compensate for feeding resource difficulties (poor quality of food, accessibility) linked to urbanization, and their behavioral flexibility allows to achieve similar breeding performances in rural and urban areas.

One of the characteristics of urban green spaces is the presence of a majority of exotic plants and trees. The consequence could be directly observed at the level of the community composition (e.g., more "coniferous" birds in town than in rural areas – [15]) as well as at the level of feeding behavior. For example, the bees give a more rich honey in town linked to the great diversity of exotic flowers. The quality of some urban food (richer, more fat) involves also some differences in individual morphology, and obesities can be observed in urban animals [35].

Wild predators are present in towns: foxes or stone martens are more common in suburbs but also sometimes in downtown [28]. Birds of prey such as falcons or sparrow hawks are today present in numerous European cities and some have adapted to the urban constraints changing their food items. The kestrel that eats small mammals in rural areas hunts particularly sparrows in towns. But the most important predator in town remains the domestic cat that eats numerous small birds (robins, house sparrows, . . .), small mammals (shrew, vole, . . .), and fragile lizards [22, 78].

Reproduction

In the same way than for food availability, the possibility to find nesting places explains the settlement or not of the species in the urban areas. For example, the study of breeding birds in town shows clearly the absence of birds of open habitats, especially ground-nesting species such as larks [15], that need high grass and quiet places. Lancaster and Rees [38] found that cavity nesters were at an advantage in cities. However holes (in building or in trees) seem very dependent of the history of the building or of the park. The number of cavities in building appeared rapidly decreasing with the new architecture and the protection of all walls. In addition, linked to the hard urban disturbances, birds nest the higher possible and the installation of nest boxes (that are generally not sufficiently high) do not resolve always the problem of the lack of cavity. However, the management of parts of public parks in a more ecological way (especially increasing shrub plantation) favors the availability of the nesting places for numerous passerines. In the same time these sites become progressively more acceptable for a small fauna of soil, litter, grass, and shrub.

The reproduction success is highly variable according to the species. Urbanization profoundly affects the reproductive parameters of birds [9]. Mennechez and Clergeau [47] observed in starling that (1) although the rate at which parents feed their nestlings was higher in urban areas than in rural ones, the amount of food delivered to nestlings by parents in town was weak and (2) the body mass of nestlings reared in the urban sector was significantly lower. This supports the idea that urban nestlings received insufficient food loads or food of low quality (refuse food). Urban environment imposes severe constraints in terms of nutritional "conditions." So some generalist birds such as starling can have bad reproduction in town when generalist species such as the kestrel can have good urban breeding performance [36]. It seems difficult to generalize a relationship between habitat generalist and specialist, without integrating the capacity of adaptation of the different species.

Territorial Behavior

The behavior of wildlife in town is not well studied and today only some mammals have been seriously analyzed. For example, it is well known that cats change their social organization and their territorial behavior in town. In natural and in rural areas, wild cats or domestic cats each have a stable home range with only some spatial overlaps; the organization avoids all possibility of temporal contact. In town, the social organization is absolutely changed: Cats leave in group with one or two dominant males. The impact of punctual and abundant source of food (by human feeders) explains this structure [40].

The fox has been well studied and comparison between rural and urban are conducted in several countries (e.g., [31]). All the studies give the same results: The territory of urban foxes is smaller in town and changes regularly of place. The higher mobility of urban foxes is linked to the high mortality that involves change of individual and permanent reorganization of territories, but also to the shelter availability. In town the majority of fox holes do not exist and animals sleep during the day just in flower clumps, within pipeline, under bridge, etc.

Alien and Invasive Species

Numerous exotic animals and plants have settled into new geographical regions after voluntary or involuntary releases by humans. Although only 1% of alien plants have established populations and spread (Williamson 1996), this percentage can reach 15–50% for vertebrates [34]. When these alien populations increase in number, they often exert negative pressures on the native ecosystem, especially in terms of predation or competition with native species [75]. However, in numerous cases, the mechanisms underlying their success and the potential impacts of these aliens are not sufficiently well documented. The urban areas are the first source of introduced species [16] for plants with horticulture and garden plantation, and for animals with trade of pets. This process becomes an important point of biodiversity management also in town with the goal of urban corridors permitting the dispersion from and to the town (see after).

Consequently, a change in the work of landscape gardeners is awaited in order to limit the use of exotic species known as invasive in new garden and park management. This is especially important for site adjacent to rural and natural zones.

For animals too, the trade need to be examined but also the behavior of citizen that releases all kind of exotic pets. One recurrent human behavior that seems to facilitate the establishment of exotic species in temperate regions and often in town is the supplemental provisioning of food. The provisioning behavior is observed for numerous exotic mammals (e.g., Coypu *Myocastor coypus*, Siberian chipmunk *Tamias Sibericus*, Grey squirrel *Sciurus carolinensis*), and birds (e.g., Mute swan *Cygnus olor*, Rock dove *Columba livia*, Rose-ringed Parakeet *Psittacula krameri*) and it could be one of the keys to the success of these species. Limiting the supplemental feeding of alien species could be an element of management for some invasive species and needs to be evaluated [13].

Urban Survival Strategies

Blair [4] working on birds and butterflies defined different kind of species according to their ability to colonize and settle in the town. He recognizes species that avoid the urban areas (the "avoiders" that are never present in this habitat) from species that exploit the town (the "exploiters"). These exploiters are generally "adapters" that modify their behavior to exploit better the town. Urban environment seems to impose so many constraints on birds (e.g., landscape fragmentation, isolation of habitat patches, noise, pollution, type and availability of food resources, human activities, vegetation quality in habitat patches. . .) that only species that have a (pre-) adapted way of life are able to tolerate them. Croci et al. [15] suggested that the urbanization filters bird species on the basis of their traits. That biological filter effect of urbanization seems to be a key determinant explaining which passerines can be found in town, urban adapters, and which cannot, urban avoiders. Studying bird avifauna at local and regional levels in France, Croci et al. [15] found 45 urban adapters that were mainly species that preferred forest (15 species) or meadow (14 species) habitats rather than open landscapes or aquatic habitats. The habitat availability in cities is a key determinant of the biological filter that urban constraints play on bird species from natural areas. Global abundance of species is not the main factor explaining their presence in cities. Indeed, urban adapters and avoiders were not associated with any of the modalities of the number of species pairs. Geographic distributions of urban adapters were especially wide and involved more diverse biogeographic areas than urban avoiders generally from temperate climates.

Most species with high nests are associated with tree availability and, therefore, forest habitats, whereas nesting at low or medium heights is often correlated to shrubby, aquatic, or open and appeared as gregarious species. Being with congeners landscapes, omnivorous species were at an advantage in town, whereas granivorous species were at a disadvantage. Eating a variety of food items permits an exploitation of new resources linked to the town, such as garbage. Croci et al. [15] observed also that at the contrary of urban avoiders, urban adapters did not especially present a plumage coloration dimorphism and that urban avoiders were associated with more than two clutches per year and less wingspan when compared to urban adapters. Urban adapters seemed to have larger life expectancy than urban avoiders and were more sedentary that may enhance opportunities to learn from others birds experience, for example, for food location or predation avoidance, and thus, be at advantages in new environments such urbanized areas. Urban adapters also molt once a year whereas urban avoiders molt two times. All these traits lead us to believe that during the breeding season, urban avoiders have not much resources as urban adapters to allocate for adaptation to urban areas.

Homogenization

Biotic homogenization is the process by which the similarity of a biological variable increases across time and space. According to the nature of the variable, homogenization is qualified of taxonomic when there is an increase of the similarity of species between biotopes, functional when there is an increase of the similarity of biological traits (e.g., biological characteristics), and genetics when there is an increase of the similarity of the gene pool.

Each eco-region presents its own pool of species; however, in town the species are often the same [5]. McKinney [44] suggests that the urbanization modifies the community of species, decreasing the specialist species (increasing the generalists) and increasing alien species. Consequently, the similarity between community increases with urbanization and gives biotic homogenization. In USA the part of alien exotic species is high and can explain a large part of the homogenization; in Europe, alien species are not so numerous [11] and the homogenization is linked to the increase of similar generalists. The explanations could be obtained in the similarity of the urban variables through the world (light, buildings, laws, climate, etc.).

Opportunities to Connect City Actors with Urban Nature

City Planning

The overall shape of cities has a large impact on the extent to which wildlife can colonize city environments, and to which humans can experience these plants and animals. On the one hand, there are the circular-shaped cities, of which the urban fringe – the zone where city and rural nature may interact – is minimal. Besides, the distance from the rural habitats to the city center of such cities is large, and as a result wildlife has to overcome many barriers to colonize inner-city areas. On the other hand there are starfish-shaped cities, where in between built-up areas there are so-called green wedges that may penetrate all the way to the city center. These green wedges often are remnants of former natural stream habitats or other, linear-shaped natural structures that were conserved during the urbanization process. In these starfish-shaped cities, wildlife can much easier migrate through the city environment. Moreover, for citizens the proximity of green in these green-wedge cities is much higher than in circular-shaped cities.

At a next level, it is the design of the "green within the urban area" that has great influence on the abilities of citizens to interact with nature. Within the domain of green space planning, the city's internal major green structures are planned. The challenge is to find a balance between the portions and configuration of built-up area and those of urban green. From an estate development point of view, one could aim for a maximum portion of built-up area. Although this seems economically favorable at first sight, from a quality-of-life perspective a minimum amount of urban green is demanded to make that people like to live and work in such cities. Urban planners and landscape architects, therefore, plan for green structures as public gardens and parks in between new residential and business areas to provide recreational opportunities and support the visual qualities of the built-up areas.

From the wildlife point of view, the way in which green structures are planned is crucial. Not only the amount and size of green structures, but also their mutual cohesion and their connectivity with the rural hinterland determines the habitat suitability of city environments. If urban planners aim to optimize human-nature interactions in the city, they should consider that continuous green structures are best to support wildlife movements, and thus enable plants and animals to inhabit the areas where people live and work. Thereby, wildlife will not discriminate between public or private green (as long as the habitat quality is fine), so connecting public parks with private garden complexes would favor wildlife [29].

Another aspect to take into account is that different plant and animal species may use different parts of the urban green as their habitat. Forest species (like woodpeckers) perceive large open green areas (e.g., grassland or swamps) as nonhabitat and rely on forest and trees structures for their habitat and dispersal opportunities. Other species may prefer swamp vegetation of river banks (e.g., dragon flies), or the flower-rich vegetation of extensive grassland (e.g., butterflies). To support a rich diversity of plant and animal species in the city environment, interconnecting similar types of biotope (forest with forest etc.) is necessary.

To some extent, peri-urban areas may determine the richness of urban nature. Peri-urban areas are the rural areas that are located adjacent to the city. Snep et al. [65] illustrated for butterflies that such peri-urban areas could act as source areas to strengthen nature in the inner-city. With sufficient habitat (in quality and quantity), local butterfly populations may thrive. A surplus of these butterflies may disperse from the peri-urban areas into the city using the urban green structures as dispersal corridors. City planners could take advantage of the natural value of the peri-urban area by tuning the type and structure of the urban green with the peri-urban nature. By doing so, they may optimize the opportunities for peri-urban wildlife to colonize the city.

Different Opportunities for Different Parts of the City

The public green and water structure in cities can be considered as the basis for the city's ecological functioning, due to its size and connectivity. Public green areas with predominantly lawn and solitary trees have little habitat value for the urban wildlife and its experience by citizens. If the urban green is however designed and managed in a more ecological way, a whole array of plant and animal species can be accommodated. Especially the abundance of brush and shrub vegetation containing native plant species will contribute significantly to the habitat quality of the urban green. This is, as these vegetation layers act as reproduction habitat for birds, butterflies, dragon flies etc. Also, the banks of streams and other urban water bodies have a good potential for wildlife, if not "engineered" with concrete sheet piling.

For most citizens, urban parks and water bodies are the places where "urban nature" can be experienced. Although these public areas can make up an important contribution to the city's wildlife habitat, there are other, often private, areas that have good capacities to enhance the experience of urban nature by citizens. These areas are residential neighborhoods, school environments, and business districts.

Residential Neighborhoods A good way to (re)connect humans with nature is to enable citizens to experience nature in their own backyards. Many people like birdlife around their houses (especially songbirds), a conclusion that can be derived from the large portion of residential gardens with bird feeders and nesting boxes [17]. Abundant and diverse birdlife, however, is depending on more factors than only these specific bird features. To attract birds to residential areas, there should be enough habitat (being "urban green") in and around houses so birds have opportunities to eat, rest, reproduce, and gather. A high portion of urban green, as well as sufficient variety in plant species and vegetation structure, do not only enhance bird life, but also other animal groups as mammals (e.g., hedgehogs, bats) and insects (butterflies, (bumble)bees) (Fig. 6). Plants provide different habitat functions as food source (e.g., host and nectar plants for butterflies) and as reproduction or resting place (e.g., shrub and trees for bird nests). Native garden plants generally provide more habitat value for biodiversity than exotic garden plants, as the local animal life has coevolved with native plant species. Some exotic plant species are exceptions, like the cosmopolitan Butterfly bush (*Bhuddleja davidii*) that is a nectar source for butterflies in many parts of the world.

Incorporating small water bodies (garden ponds) in the gardens and neighborhood green structures adds extra habitat value to residential areas. Water habitats offer habitat for species with an entirely aquatic way of life (like fish and water plants), and also provide places to drink and forage for many terrestrial animal species. Additionally, they offer reproduction and nursery habitats for species with a partial aquatic way of life (e.g., amphibians, dragon flies).

On average, private gardens are too small to accommodate enough habitat, for example, a bird's territory. Animals therefore move between gardens to visit different resources. The urban design of the residential area as well as the vicinity of larger urban green areas have a great impact on the extent to which

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 6
Urban green in the ecological housing area The Cherry Garden (NL), designed and maintained such that both biodiversity conservation as biodiversity experience is supported. The nectar plants and shrub provide habitat for butterflies, (bumble) bees, and song birds, the whole setting with the residential area is inviting for citizens to really experience the wildlife (Photo: Robbert Snep)

resources in a particular garden will be used by animals. If gardens are clustered, and fences between the individual gardens are permeable for wildlife, animal abundance will be more likely than in cases where gardens are walled and isolated from other green. Also, the presence of larger urban green areas in the vicinity of residential areas increase wildlife abundance, especially as there good opportunities for wildlife to exchange between urban green areas and residential neighborhood.

Finally, if wildlife is present in residential areas this does not automatically mean that citizens are aware of their presence, and as such are able to fully experience the diversity and phenomena of plant and animal life. On average, citizens often have low abilities to detect the presence of wildlife, as more and more citizens lack a history of growing up with wildlife [48]. There are two ways to increase wildlife experience opportunities:

1. To improve the visibility of wildlife for citizens, create habitat resources for wildlife in such way that wildlife will expose itself (to some extent) to citizens. Well-known examples are nesting boxes and feeders for birds, other examples are bee trap nests, nectar hot spots for butterflies (e.g., group of butterfly bush), and garden ponds. A more sophisticated way is installing webcams in bird and bat boxes, or infrared cameras for nocturnal wildlife.
2. To improve the wildlife detection ability of citizens. Educate citizens in detecting wildlife, using binoculars (birds) and netting (insects, aquatic life) and tracking (ground-dwelling mammals) techniques. Often, (local) conservation groups are best equipped to stimulate and educate people on wildlife monitoring, using citizen science for conservation purposes.

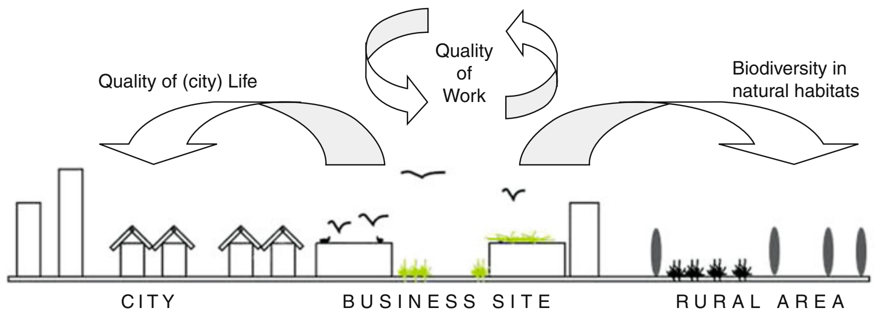
School Environments Richard Louv [41] wrote a well-known and inspiring book, entitled "Last Child in the Woods," addressing the rapidly decreasing experience of (urban) youth with nature. This book gives a plea for (re)connecting youth with plant and animal life. School areas are perfect places to do so, as children

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 7
Greening project at a primary school, together with the children. Plants with added value for biodiversity are planted (*left*), attracting small wildlife that can be experienced (*right*) (Photo: Soontiëns Stadsnatuur)

will spend a large part of their early years in these environments. School yards can be designed and managed such that wildlife experience is optimized. Replacing a part of the school yard tiles by urban green that has good habitat value for butterflies, birds, (bumble)bees will stimulate children to explore nature. By actually involving children in the realization and management of this "school nature," they will perceive it as "their own" nature (Fig. 7).

Not only at school yards but also at other places in the direct vicinity of schools there are opportunities to let children experience wildlife. In the Dutch city of Eindhoven, more than 20 primary and secondary schools participate in the "school pond project," a municipal project in which ponds and nearby schools are managed and monitored by youth, supervised by local wildlife experts and teachers. During classes the children visit the ponds, making sure they are well informed about the developments of the local nature. If necessary, additional conservation measures such as habitat improvement are executed to enhance populations of local plants and animals. Linking the outdoor school nature with the actual school lessons on environment and biology offer opportunities to provide more background information about the local wildlife, and support children to understand the diversity of life and the working of the ecosystem.

Business Districts "Business districts" can be further classified as high-quality business sites, mixed business sites, logistic areas, heavy industrial areas, and seaport areas. Other names for these areas are business sites, business parks, industrial sites, industrial districts, or industrial estates. Opportunities for business sites to provide ecosystem services are now gradually being recognized. For example, recent studies have focused on how flat roofs, a typical feature of business site buildings, can be used (designed as green roofs) to reduce urban air pollution [80] or road traffic noise. Regarding biodiversity conservation at business sites, some initiatives are already under way in current practice. The US Wildlife Habitat Council (WHC) encourages corporations to voluntarily manage lands for wildlife and biodiversity protection, and certifies companies that substantially contribute to biodiversity conservation on their corporate lands [76]. Cardskadden and Lober [8] studied the benefits to corporations of participating in the WHC programme in terms of its influence on relationships with key corporate stakeholders including employees, host communities, environmental groups, and regulators. They report that at 164 sites, 95% of respondents indicated that wildlife habitat programs had led to improved employee morale; 72% indicated improved relationships with environmental groups; 60% noted a positive effect on



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 8
Overview of how the greening of business sites with vegetation attractive for wildlife may improve both the business site as its urban and rural surroundings. The quality of life in adjacent residential areas can be enhanced by common wildlife originating from the business site [65]. The quality of work can be improved as the green enhances the aesthetic and recreation perception in the business environment [64]. The biodiversity in natural habitats near the business site can be enhanced as the business site may offer specific habitat for endangered butterflies and other species [66]

community relations; and 49% of respondents reported improved relations with regulators. These benefits were in addition to the annual cost savings reported by 50% of the programs. Besides, relationships with the community, government, and environmental groups led to better wildlife programs due to increased expertise.

In another example, the UK British Trust for Ornithology (BTO) awards companies that take specific measures to conserve bird diversity on their lands. The Business Bird Challenge began in 1994 and is a partnership between businesses, the BTO, and local communities which encourages biodiversity on business and industrial sites. Sites range from working quarries, power stations, and oil refineries to research establishments, company headquarters, and restored nature reserves. The aim is to maximize the potential of business sites for birds and other wildlife whatever the business site size.

In the Netherlands, Dutch Landscape Management promotes the integration of landscape elements and species conservation measures into business site development. They aim to raise awareness among municipalities and the business community, but also among project developers and designers, regarding opportunities and advantages that "green" business sites offer. They thereby focus on fitting business sites into their surrounding landscape, enhancing the ecological significance of business sites and increasing the accessibility of the sites for recreation purposes.

Business sites, often located at the city's edge, can offer habitats for rare species (e.g., pioneer butterflies and amphibians), which mainly occur in the surrounding rural landscape, and for common species that also occur in the city [63, 65, 66] (Fig. 8). This implies that if biodiversity conservation is incorporated in business site planning, design, and management, the effectiveness of investments in conservation measures will increase if the target species and type and amount of habitat are attuned with the regional context of ecological networks.

Biodiversity conservation at business sites can be shaped in different ways, each with its own (socio) economic and environmental characteristics. There are different options for biodiversity conservation at business sites: green roofs and walls, a more ecological management of the conventional business green, temporary early successional vegetation on vacant parcels, and the design of ecological corridors and stepping stones throughout the business site. Results from a stakeholder survey on this topic suggest that implementing measures to enhance biodiversity may be acceptable only if combined with other green functions (predominantly "recreation" and "health and well-being") and if suited to the functional appearance of the business site environment ("external appearance" and "tidiness") [64] (Fig. 9).

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 9
Left: Illustration of how vegetation with ecological value (e.g., nectar plants) can be designed for a business site environment. *Right*: Actual urban green patch at a company with host plants for caterpillars of the Swallowtail (*Papilio machaon*) (Photos: Soontiëns Stadsnatuur)

Future Directions: Integrating Wildlife Conservation in Sustainable City Planning and Design

Future directions in research, education, and practice on integrating wildlife conservation in sustainable city planning and design may focus on:

1. Climate-proof city green with ecological value
   According to Pauleit et al. (see chapter "► Green Infrastructure and Climate Change") urban green may support the resilience of cities toward climate change, as vegetation is able to cool (evaporation, shade) city environments and storage storm water (pervious soil). This demand for additional, climate-proof, urban green opens an opportunity to enhance the ecological quality of the city, if executed in the right way. As example, green roofs have excellent capacities to deal with heat and storm water (see chapters "► Green Roofs, Ecological Functions" and "► Green Roof Infrastructures in Urban Areas"), however the *Sedum* monoculture roof type – that is currently applied at large scale – has less ecological value than green roof types with more diversity in plant species (preferably, native), soil type, and depth and other characteristics. A challenge for the future therefore is to design and manage the urban green meant for climate change mitigation purposes in an ecological way.
2. Urban agriculture with ecological value
   Allotment gardens in city environments are an ancient phenomenon, subject to societal trends and thereby increasing and decreasing in popularity over time. A whole new global trend is the concept of urban agriculture, beyond the traditional allotment garden. Urban farms produce food for the city, within the city itself. A well-known and quite extreme example are the urban farms at roof tops in New York City. Urban farms appeal to the current demand for "home-grown food."

   Urban agriculture provides habitat opportunities for urban wildlife and wildlife experience, if the agricultural practices are based upon biological principles (e.g., no pesticides). Urban farmers as well as visitors of these farms will thereby experience how natural processes like pollination are essential for growing food. Though this used to be basic knowledge among people for ages, citizens often have lost this knowledge. Urban farms are therefore excellent places to teach citizens about vital ecosystem services such as pollination and biological control. A future challenge is to integrate the urban agriculture concept in the city planning and design, as such that this phenomenon contributes to the basic understanding of citizens about the natural world they live in.
3. Urban energy and commodity production with ecological value

Biodiversity in Cities, Reconnecting Humans with Nature. Figure 10
Green roof vegetation at an inner-city apartment block in Eindhoven (NL). A nice appearance of the green is combined with a plant choice and maintenance that supports wildlife (birds, butterflies) and its experience by the residents (Photo: Soontiëns Stadsnatuur)

With successive energy and commodity crises worldwide, urban regions start to explore possibilities to produce their own energy and commodities, thereby decreasing their dependence from energy and commodity producers outside their region. There are several ways to produce energy, using different techniques.

One way to generate electricity or commodity comes from biomass. Although urban regions in general have a low production of biomass (e.g., prunings of tree and shrub vegetation from urban green management), this method may enhance the citizens' awareness about energy ("burning") and commodity ("biorefining") production, and also provides an added value to the city green. If in the near future urban biomass targets are set, this may lead to more shrubs and trees in the city, meaning more habitat for wildlife. The biomass topic represents future benefits that urban green may provide and that are currently not taken into account by urban planners and landscape architects in city development (see also chapter ► Urban Forest Function, Design and Management).

Another way of producing energy in cities is by solar panels at roof tops. These solar energy systems work most efficiently if the outside temperature is not too high. At roof tops covered with bitumen, the temperature will increase too much for optimal functional of the solar panels. At green roofs the direct surrounding of the solar panels is cooled by the vegetation (evaporation) and thus there is more efficiency.

Snep and Opdam [62] and Beatley [3] have addressed the opportunities to integrate natural values in urban planning and design quite extensively, like in Fig. 10. These publications focus on the "nature" aspect of urban green. There is however a much larger, global trend of "green cities", in which "nature" is not mentioned explicitly. The term "green" here refers to "sustainable" ("green" being a modern alternative) or "vegetated" ("green cities" uses urban vegetation for its societal benefits). A challenge may be to connect these two worlds, to enable planners, (landscape) architects, project developers, and others to integrate wildlife conservation in the planning and design of sustainable cities. Future directions as mentioned above (climate-proof, urban agriculture, urban energy) can be seen as starting points to come to green, ecological cities with contain mutual benefits (both sustainable and natural).

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Biofuels and Sustainable Buildings

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Article Outline

Glossary

Alcohol A compound in which the –OH group is connected to an aliphatic carbon atom.

Biofuel General classification of a fuel refined from recently harvested organic matter.

Biomass The solid form of biofuel.

Biogas The gaseous form of biofuel.

Bioliquid The liquid form of biofuel, ethanol, and biodiesel.

Catalyst A substance that enables a chemical reaction to proceed at a usually faster rate or under different conditions (as at a lower temperature) than otherwise possible.

Cetane number A measure of the ignition quality of diesel fuel and influences combustion characteristics.

Feedstock The raw material that will be processed into a fuel.

Petrol-diesel Diesel fuel that is derived from petroleum.

Pour point The temperature at which a liquid stops behaving like a liquid.

Transesterification The process of converting one ester into another ester using an alcohol and oil.

Definition of the Subject and Its Importance

Biofuels come in many forms and from a variety of sources. The biofuels may be solid (biomass), gas (biogas), or in liquid form (biodiesel, ethanol, etc.). Biofuels may be derived from most plant material as well as some animal parts, typically animal fats. As plants grow over much of the world's landmass and their primary source of energy is the sun, biofuels are abundant and renewable. Furthermore, as biofuels absorb the sun's energy to grow, biofuels are nature's solar energy battery.

Biofuels have been used for thousands of years as a source of heat and light for civilization. However, as humanity's energy consumption has become more sophisticated, fossil fuels have gained a technological edge in refining and supply chain management. For the last decade, renewed interest in biofuels has increased the adoption of biofuels for making heat and electricity. The drivers for the interest in biofuels are many; including energy security, environmental concerns, and economic competitiveness.

To address all these interests, the entire life cycle of the biofuel and its use must be considered. Energy security or establishing an effective/reliable supply of biofuels is a must for any building operator considering biofuels as a primary fuel source. Pollution concerns may drive a building operator toward or away from biofuels. For example, soy-based biodiesel reduces particulate production in an engine generator; however, NO_X emissions may increase. Both particulates and NO_X are regulated emissions and a building operator will need to be aware of the implications of their fuel choices. Economic concerns are important for most building operators. A fuel source with a competitive/stable price is highly sought after. As recent history has shown, most fuels do not appear to be immune from macroeconomic price influences as was seen in gasoline and ethanol prices in the late 2000s.

Biofuels can be used to generate heat in boilers or both electricity and heat in engines, gas turbines, etc. Biomass in the form of wood pellets or chips are used with some frequency in residential and some commercial heating applications and a number of manufacturers of pellet and chip burning heating systems are on the market. Larger boilers may use biodiesel in place of fuel oil or biogas in place of natural gas to make larger quantities of heat.

Biofuels have also been used to make electricity and heat in power plants of a variety of sizes. Large amount

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of biomass such as sawdust are burned in boilers to make steam to drive a turbine, which in turn generates electricity. Smaller applications include using biodiesel, ethanol, and biogas in engine generators and gas turbines to provide backup power or primary power and heat. Similar to the wood chip and pellet burning, there are several manufacturers of engines and gas turbines that offer systems capable of using biofuels for building applications.

Introduction

Biofuels have been used for thousands of years to make heat and light; however, recent political, economic, environmental, and security concerns have refocused the world's attention on biofuels of all types.

The majority of attention is focused on biofuel for transportation purposes; however, as the U.S. Department of Energy has stated that, 40% of energy consumption and emissions come from building operations [1]. To alleviate the environmental impact of building operations, world governments, researchers, and building designers are looking for ways to reduce the carbon footprint of buildings as well as finding alternatives to dwindling supplies of fossil fuels required to operate modern buildings.

The building owner/operator should be aware of the entire life cycle of the selected biofuel to avoid any operational disruptions of embarrassment that may arise from a less efficient part of the biofuel delivery process. For example, high-quality palm oil may be very desirable for a boiler. However, if that palm oil comes from a plantation, where a rainforest once stood and was burned to the ground, the environmental benefit of that palm oil would be in doubt.

The life cycle of a biofuel is broken down into five parts, each of which has several considerations:

- Growth
  - How fast does the feedstock grow?
  - How much energy is derived per pound of plant material?
  - How much energy does it take to produce the plant material?
  - Where does the plant material grow?
  - What grew in this location before the biofuel crop?
- Harvest
  - What methods of harvesting the plant material are used?
  - Does the method of harvesting use more energy than the biofuel generates?
- Refining
  - Does the refining process generate large waste streams?
  - How much energy does the refinement process consume?
- Distribution
  - Does the shipping of the biofuel consume more energy than the biofuel generates?
- Use
  - How efficiently is the fuel being burned?
  - Is the fuel being burned cleanly to meet emissions standards?
  - Is the fuel being stored properly and safely?

The building owner/operator is most directly impacted by the "Distribution" and "Use" phases of the life cycle analysis, but as stated other parts of the life cycle may be significant to the user of the biofuels and undermine their broader sustainability goals.

Growth

Different sources of biofuels grow at varying rates, in varying conditions, with varying amounts of required resources. Needless to say, not all biofuels are created equally. For example, Fig. 1 shows the quantity of oil per unit area for many different types of crops. See reference for a more complete listing of plants.

While the actual input energy for growing an acre of crops varies depending on location and technology, it is clear that some crops are better than others for creating energy and the users of this energy should be aware of their impact. This same concept applies to biomass and biogas, where there can be great variability depending on the feedstock, which should be discussed with the fuel supplier.

Plant	Latin Name	kg Oil/hectare	lb Oil/acre
Corn	Zea Mays	145	129
Palm	Erythea Salvadorensis	189	168
Cotton	Gossypium Hirsutum	273	243
Soybean	Glycine Max	375	334
Pumpkin Seed	Cucurbita Pepo	449	400
Mustard	Brassica Alba	481	428
Sunflower	Helianthus Annuus	800	712
Peanut	Arachis Hypogaea	890	792
Opium Poppy	Papaver Somniferum	978	871
Rapeseed	Brassica Napus	1,000	890
Castor Bean	Ricinus Communis	1,188	1,058
Jatropha	Jatropha Curcas	1,590	1,416
Coconut	Cocos Nucifera	2,260	2,012
Buriti Palm	Mauritia Flexuosa	2,743	2,442
Macauba Palm	Acrocomia Aculeata	3,775	3,361
Oil Palm	Elaeis Guineensis	5,000	4,452

Biofuels and Sustainable Buildings. Figure 1
Average production rates of vegetable oils by plant type [2] (1 kg/ha ≈ 0.9 lb/acre)

Refining

Most of the processes to create biofuels are conceptually simple; however, the creation of high quality, certified biofuel typically requires specialized equipment and skilled personnel to carry out the process. The text below will outline the basic process for refining biofuels; however, the refinement steps required to make certified fuels are typically much more demanding.

Biomass

When using biomass as a primary energy source it is best to refine the fuel somewhat rather than just cutting down a tree and throwing it into a fire. Most biomass contains a significant amount of moisture, which reduces combustion efficiency and increases particulate and carbon monoxide pollution. As the moisture in the wood evaporates due to the heat from the fire, it displaces oxygen thus reducing the combustion efficiency, which is directly related to the amount of oxygen available. Therefore, wood is often dried prior to being supplied for use in commercial boilers.

In addition to drying the biomass, it is often pelletized or broken down into smaller pieces or chips. This simplifies distribution of the product and simplifies automatically feeding the biomass into boilers. Making smaller pieces of wood also aids the combustion process by making it easier for air to get to the fuel for burning cleanly.

There are many other types of biomass that have various refining methods, from sawdust at lumber mills to grass clippings and tree trimmings burned in an incinerator, but these are more customized systems. The wood chip or pellet burning boilers are the most common application of biomass fuel use in buildings.

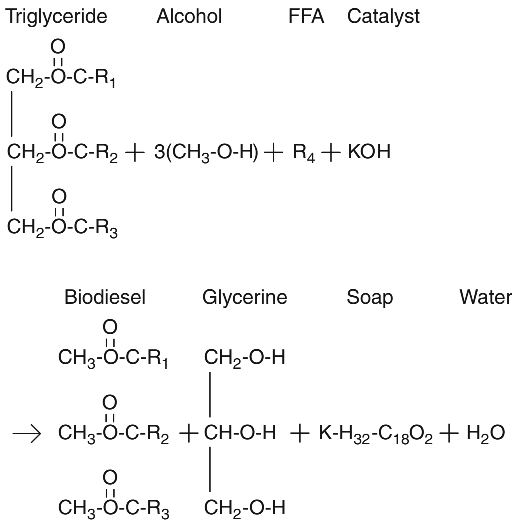
Bioliquids

Bioliquids (biodiesel and ethanol) are more complex and require a basic knowledge of chemistry. Ethanol is made like any consumer alcohol through fermentation of sugars. Most commonly these sugars come from corn or sugar cane. The ethanol is then denatured to prevent the ethanol from being used in food products to avoid alcohol taxes which would significantly alter the price of ethanol.

Pure ethanol can be used directly in some engines; however, more commonly an 85% ethanol/15% gasoline mixture known as E85 is sold in the USA and can be used in vehicles with flex fuel engines. Flex fuel engines are defined as engines that can use multiple fuel types and grades. Currently, all modern vehicle engines sold in the USA can already accept up to 10% ethanol mixed in with the gasoline.

At this time there are no commercially available E85 boilers or generators; however, ethanol is the most common biofuel available in North America with its primary use for transportation.

Biodiesel is also mostly used for transportation purposes; however, more boiler and generator applications exist as it is more similar to standard Diesel fuel than E85 is to gasoline. Biodiesel is refined in a process known as transesterification. This process includes combining almost any vegetable oil or animal fat with an alcohol and a catalyst. The types of oils used are known as triglycerides, which are long-chain fatty acids joined by a glycerin backbone. Some of the most common alcohols used are ethanol, butanol, or methanol. The catalyst, typically sodium hydroxide or potassium hydroxide, speeds up the reaction which separates the esters. The chemical equation below depicts the basic transesterification process.



Equation 1: Basic transesterification process [3]

The two most important effects of the transesterification process are to reduce the freezing temperature of the ester and to reduce the viscosity of the ester so it can be used over a wider range of temperatures. Some older diesel engines have been observed running on heated, unaltered vegetable oil; however, newer high-precision engines require higher grade fuels, which the transesterification process provides.

Once the transesterification process is complete, a neutralizing acid is added to the system to cause the potassium or sodium to precipitate, which simplifies the processes of removing it from the biodiesel. Furthermore, the biodiesel is washed with water to remove excess alcohol from the biodiesel.

Phosphoric Acid		Catalyst		Potassium Phosphate		Water
H_3PO4	+	$2(KOH)$	$\rightarrow$	K_2HPO_4	+	$2(H_2O)$

Equation 2: Neutralizing step for the transesterification process

There are dozens of proprietary processes used commercially that have reduced the refining time and improved the yields of the refining process; however, that is beyond the scope of this entry.

Biogas

Biogas can often be found on farms, landfills, and wastewater treatment plants. The process is complex but primarily involves capturing, cleaning, and dehumidifying the methane gas that is generated from decomposing organic matter.

As methane is the primary component in biogas as well as natural gas, it can be considered a direct alternative if the biogas has been sufficiently refined. A large portion of the biogas refining process is removing siloxanes and moisture from the gas, which can cause engines and boilers to fail prematurely.

There are many commercially available boilers, engines, and gas turbines that will run off less refined biogas; however, there is a cost premium due to more expensive materials. Therefore, a balance must be struck between refining and use.

Typically biogas refineries collect a significant amount of biomass such as municipal waste treatment facilities, landfills, and farms. It is difficult to justify the installation of such a system if little biomass is available. Working with the local gas company to find a supplier of biogas may be an alternative approach to supplying your building's systems with biogas. Figure 2 shows a system that is being constructed in 2011 to supply a university with biogas from a municipal landfill.

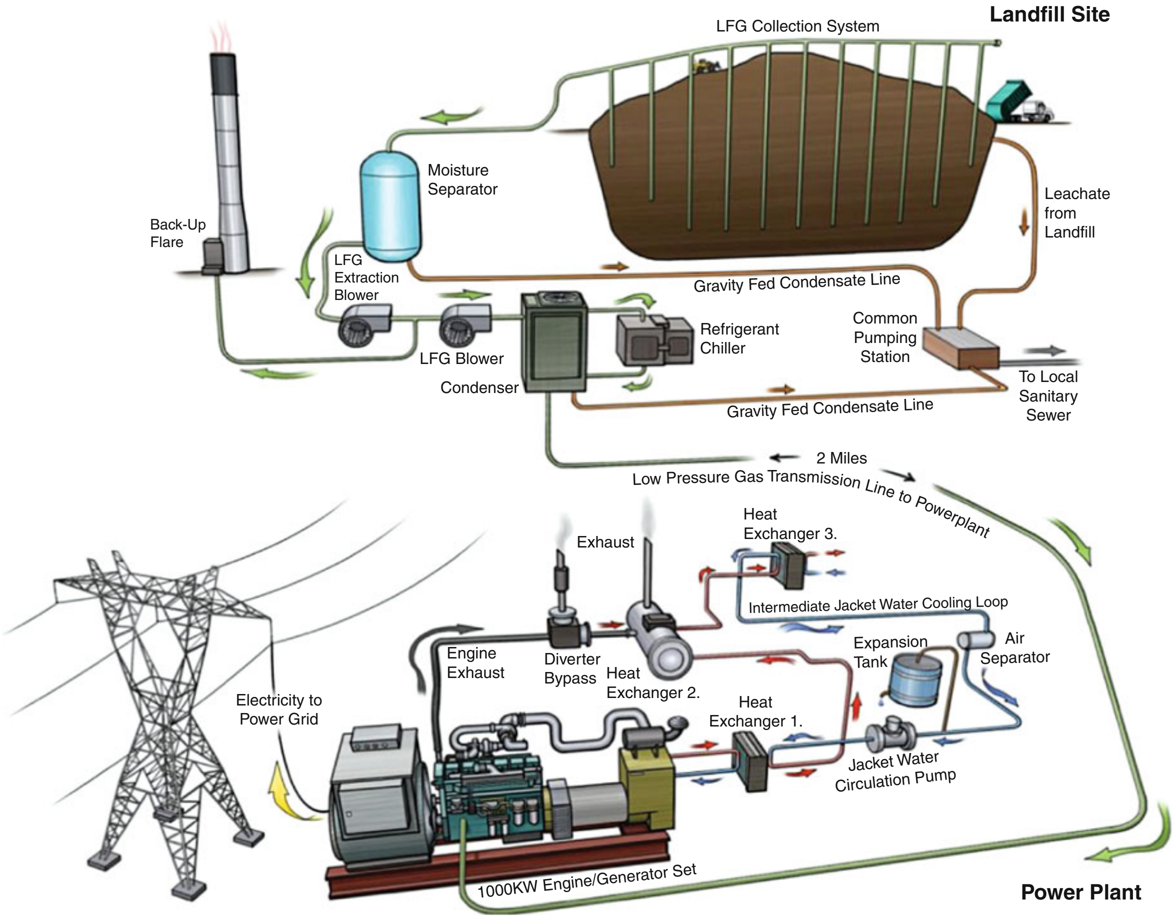
The system shown in Fig. 2 is being built in stages with the landfill flaring system being constructed first. The advantage of building the flaring system first is to determine how much gas is available before selecting the pipeline and plant size. The quantity of gas production is very difficult to predict as the exact type of waste deposited in the landfill over the last 25 years is unknown.

An alternative system is a biomass gasification system that uses wood chips and process known as pyrolysis, which burns wood chips in an environment with little oxygen as shown in Fig. 3.

The balance of the biomass gasification system may use boilers or engines coupled with heat recovery, which will be addressed in later sections.

Owner/Operator Concerns

The day-to-day operations that effect building owners and operators include the supply, storage, use, emissions, and cost of the biofuel. As stated, the issues



Biofuels and Sustainable Buildings. Figure 2
1 MWe landfill gas cogeneration system [4]

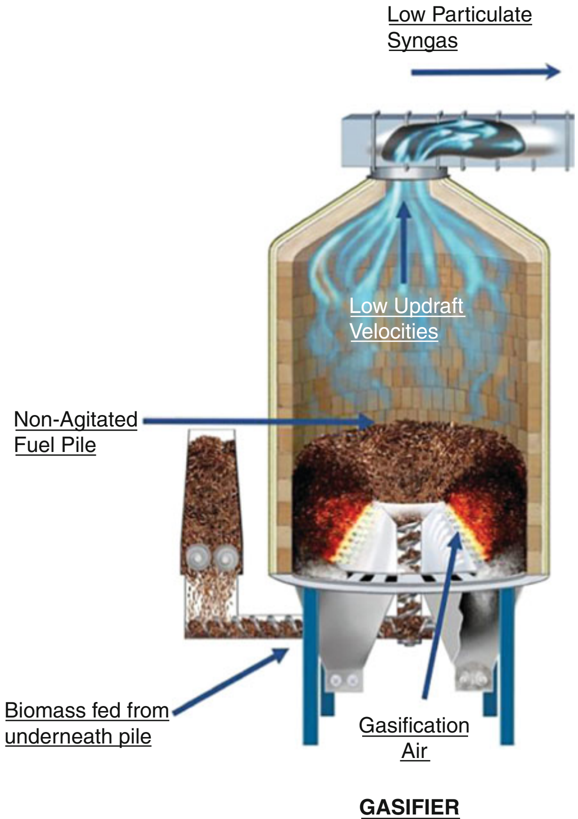
discussed in the background section should be of concern to the building owner in a holistic sense, the following sections will describe some of the challenges and considerations that directly impact the building owner and operators as well as the design team.

Supply Chain

Establishing a steady supply chain for biofuels is of vital importance to the successful operation of any system. Unlike fossil fuel distribution infrastructure, biofuel distribution infrastructure is limited and may be unreliable in certain areas for certain fuel types. There is a growing body of trade associations for commercial biofuels that can assist building owners in establishing a steady supply chain [6–8].

An alternative to commercial biofuel supply is to establish an independent biofuel infrastructure. Building designers and owners should be aware of nearby resources such as farms, waste treatment facilities, and/or cafeterias/restaurants that generate significant resources that could be converted into biofuels. While it is complex and expensive to setup independent refining facilities, it may be cost and environmentally beneficial in the long term. If it is financially feasible, a backup fossil fuel system may be desirable.

As stated in the refining section, certified fuel is often required for most biofuel burning equipment. It is important to verify that the fuel supplier is meeting the most recent fuel quality standards. The most recent standards can be obtained from the biofuel trade associations [7, 8]. These standards continue to be under



Biofuels and Sustainable Buildings. Figure 3
Biomass gasification system [5]

development and receive frequent updates as the modern biofuel industry is not as mature as the fossil fuel industry. It is essential that fuel specifications are passed on to the boiler, engine, or turbine manufacturer to determine if the performance estimates are accurate as well as if the fuel will void the product warranty.

While getting biofuels to your site is a challenge, the U.S. Department of Energy's National Renewable Energy Lab (NREL) has assembled a map to assist biofuel users in determining where high concentrations of biofuels are likely to exist. Figure 4 below shows the approximate quantity of biofuel generated per year by location.

Fuel Delivery and Storage

Fuel storage is often a necessary part of biofuel systems, and there are a number of considerations to be investigated. First and foremost are fire code requirements, as biofuels, while often safer than fossil fuels, still pose a significant risk. The fire code is doubly important if fuel refining is done on-site as well. Local fire codes may not address biofuels and therefore fossil fuel requirements may be applied or a state fire code. Most biofuel trade associations will provide some assistance in the areas of fire safety.

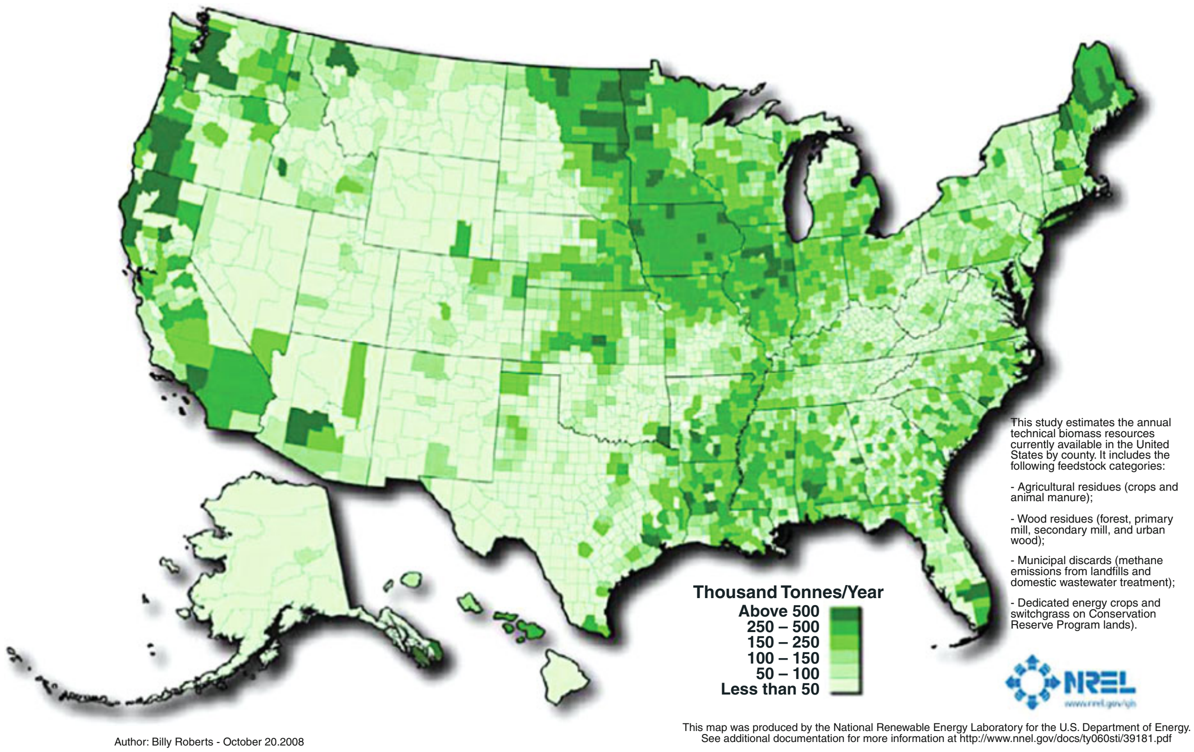
The first step in storing fuel is getting the fuel from the delivery vehicle to the storage tank. For the biodiesel and ethanol, modified gasoline and diesel delivery vehicles are typically used, and are frequently available due to the large gasoline and diesel fuel infrastructure that exists. Again, local codes will designate safety features required to fill the storage tank. Independent biogas delivery is often done the same way as a standard natural gas line.

Wood pellets and chips vary in delivery methods. As such, the fuel transfer and storage system should be coordinated with the fuel supplier prior to design and construction. Some suppliers bring trucks that literally suck pellets out of the truck via hose and shoot them into the storage container using compressed air. Other methods include small dump trucks that pour the chips or pellets into a trough where an auger will transfer the chips or pellets into a storage tank.

Biogas is rarely stored on-site as the process of getting it to site is somewhat complicated and dangerous. First, the biogas is pressurized and bottled off-site by the biogas producer. The biogas bottles are then transported by truck to the building site and stored until needed. The biogas bottles require the necessary gas regulators and explosion proof equipment to distribute the biogas to the boiler or engine that it will fuel. Biogas systems like this are typically reserved for experimental systems.

Sizing the storage tank is a function of first cost, delivery cost, and rate of fuel consumption. It will be an iterative process to balance these criteria as delivery costs and the rate of fuel consumption will vary over time as it is a function of load, which is difficult to project accurately, and projections are very difficult to make accurately. The larger a storage tank, the higher the first cost both in construction and physical space required.

Once the storage size is known, the tank materials must be selected. While no exotic or expensive



Biofuels and Sustainable Buildings. Figure 4
Biofuel potential by county for the USA [1]

materials are required to store most biofuels, some common materials can cause issues.

Wood pellet and chip storage should be in a dry, weather-protected location. However, the spaces do not need to be conditioned by mechanical systems.

Brass valves and some elastomers (rubber) used in seals may be problematic over time for ethanol and biodiesel. The U.S. Department of Energy, National Renewable Energy Laboratory has published material compatibility documents for both ethanol and biodiesel [9, 10].

Biofuel Use

The use phase of biofuels is often of greatest interest to the building owner/operator. Biofuels can be used in boilers and hot water heaters, reciprocating engines, gas turbines, and fuel cells. Most equipment manufacturers have standardized their products to work well with existing technology, making retrofits and new designs relatively simple.

Boilers/Water Heaters Boilers and water heaters are available to be used with almost any biofuel. The most common commercial products are wood pellet and chip boilers for residential use. However, larger commercial boilers are becoming more common as fuel availability, delivering, and automatic feed systems have become more refined. The smaller residential units are typically available as packaged systems and are relatively easy to install. The larger commercial units are more complicated to install as storage and delivery systems need to be tailored for each site.

Fuel oil and natural gas boilers and water heaters may also be available in biodiesel and biogas variants on a case-by-case basis. The performance of these systems will vary based on the manufacturer, but in general manufacturers of boilers and water heaters have gone to great lengths to achieve equivalent or better performance than conventional boilers regardless of fuel type.

The only noticeable change will likely be in the quantity of fuel burned to achieve the same output.

For example, the energy density of pure biodiesel is approximately 5% less than that of standard fuel oil. As such, approximately 5% more biodiesel would need to be burned to achieve the same heat output. That said, all fuels, fossil and bio, have energy density tolerances and vary in quality over time depending on a variety of factors based on the recent inputs into the refining process.

The operators need to be aware that running a boiler in a not so cold month with a lower quality fuel may consume more gallons than a colder month with high-quality fuel. That said, prices should reflect the average value of the fuel delivered over the course of a year. Therefore, the cost per unit energy may be high one month and low the next; so it will balance out. The alternative is testing each batch of fuel to determine its energy density, which would be very costly.

Some issues exist with biomass boilers during low load conditions. Strict temperature controls should be put in place to properly regulate the burning of biomass. Low burning temperatures may cause the emissions to change, and create significant carbon monoxide and particulate issues. This will be revisited in the emissions section, but some manufacturers have addressed this issue in their product designs.

Ash removal is also a concern for biomass boiler operators. Like any fire, a small quantity of ash remains that must be disposed of. In facilities with significant land available, the operators may consider dumping the ash on-site as the plants may benefit from the increased nutrients. Any use of ash on-site should be coordinated with a personnel qualified to understand how the local plants will be effected by mixing ash into the soil. Some plants and soil will benefit, while others may be harmed. Urban users of biomass will need to coordinate waste removal with the local refuse company to verify if ash can be land filled or otherwise disposed of in a safe manner.

Reciprocating Engines, Gas Turbines, and Fuel Cells (Prime Movers) The alternative to burning biofuels to create heat is to use the fuel in an engine, turbine, or fuel cell to generate electricity and heat. The function of these systems is essentially unaltered; however, the performance and maintenance may change noticeably. As of July 2009, NREL estimated that 10.5 GW of electricity was being generated with biofuels with a total potential of 78 GW [1].

Similar to the biofuel boilers and water heaters, manufacturers of prime movers (engines, gas turbines, fuel cells, etc.) have been addressing the compatibility of their products for use with biofuels. As stated in the boiler/water heater section, the energy density of the fuels may vary and the prime movers are no less affected by this difference. Often fuel pumps and capacities are oversized in many systems to account for peak demand operation. Some of this spare capacity is used to feed more biofuel into the prime mover to maintain the desired power level. For example, a Diesel engine fueled with 100% biodiesel operating at 30 kW (40 Hp) will consume fuel as if it were operating at approximately 32 kW using Diesel fuel.

Table 1 shows a selection of prime movers with some general comparisons.

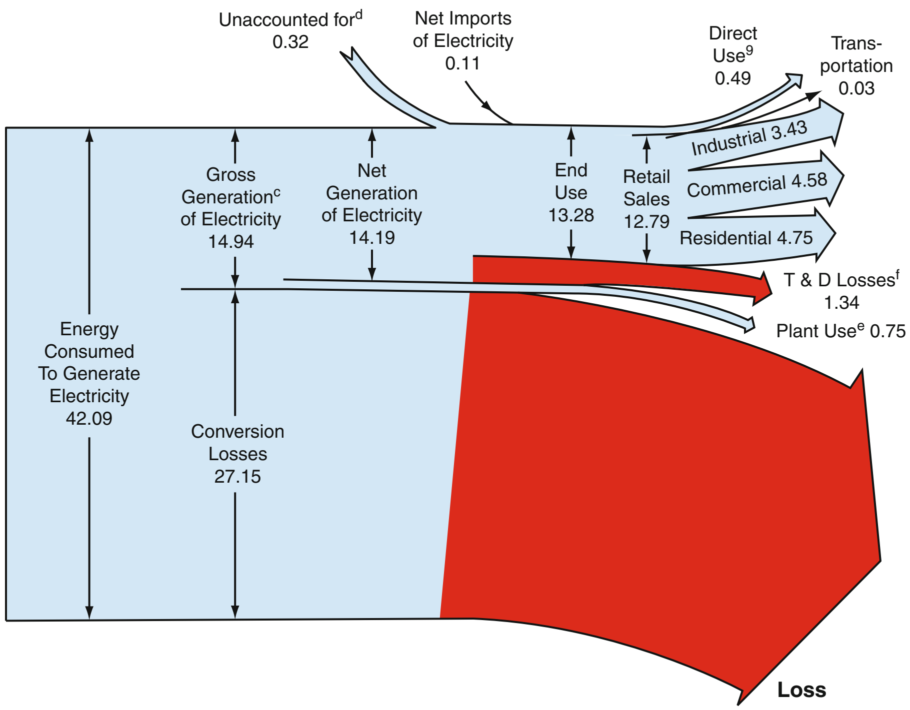
The exhaust and reject heat streams of the prime mover perform nearly identically to fossil-fueled prime movers [11]. Therefore, converting a cogeneration plant from fossil fuel to biofuel may not require the balance of plant to be altered to maintain functionality.

Changes in maintenance cycles are often the cause of the greatest failures of biofuels. For example, a building operator may have been maintaining backup natural gas engine generators for years. However, if an owner has replaced the natural gas fuel supply with biogas, the previous maintenance cycles may be completely out of sync with the new reality. If the biogas is not the same quality as the natural gas, and is somewhat more corrosive, the engine seals could break down prematurely or the cylinders themselves could start to corrode. The operator must be vigilant about system performance and perform consistent maintenance checks. Additional equipment may be required to inspect the engine as compared to a conventional gas system. As there are relatively few long-term studies of biofueled systems, it is important for the building operator to coordinate and train with the prime mover manufacturers to avoid potential failures.

Cogeneration Prime movers are often paired with heat recovery systems to make combined heat and power (CHP) systems also known as cogeneration systems. The advantage of a cogeneration system versus

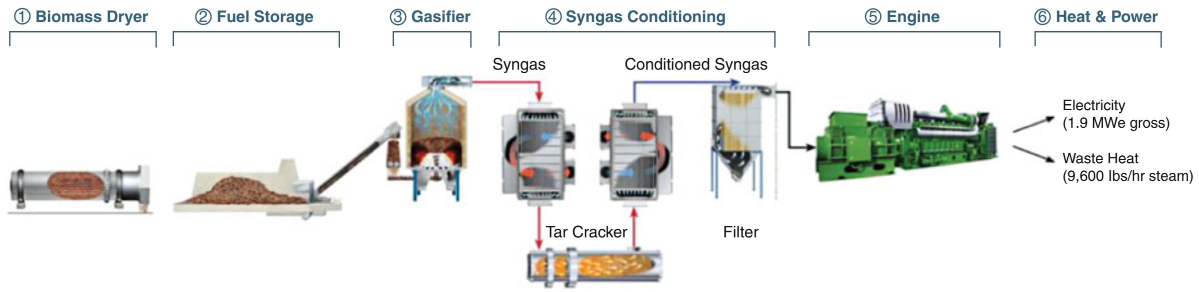
Biofuels and Sustainable Buildings. Table 1 Prime mover comparison by fuel, efficiency, and heat

Prime mover	Fuels	Electrical efficiency	% recoverable heat	CHP efficiency	Heat to power ratio
Boiler + steam turbine	Natural gas, coal, waste fuels, biomass	10–15%	45–65% low-quality steam	65–80%	4.3
Gas turbine	Natural gas, biogas	15–25%	45–55% 600°F exhaust	60–80%	2.8
IC engine					
-Diesel	Diesel, biodiesel	30–40%	15–20% 190°F coolant, 15–20% 900°F exhaust	60–80%	1.6
-Spark	Gasoline, E85, natural gas, biogas	20–42%	15–30% 190°F coolant, 15–20% 900°F exhaust	50–80%	2.0
Fuel cell					
-SOFC	Natural gas	35–45%	25–35% 500°F exhaust	60–80%	0.8
-PEM	Hydrogen	35–45%	25–35% 300°F exhaust	60–80%	0.8



Biofuels and Sustainable Buildings. Figure 5
U.S. Electric grid energy flow [12]

grid power and standard boilers is that power plants waste approximately two-thirds of the fuel energy in the form of reject heat. Figure 5 shows the energy flow for the US power grid with approximately 68% of fuel energy being lost in conversion and transmission and distribution losses. With a cogeneration system, the majority of this energy can be recovered for useful purposes such as space heating and cooling.



Biofuels and Sustainable Buildings. Figure 6
Cogeneration and biomass gasification plant [5]

The example shown in Fig. 6 shows a complete biomass gasification and cogeneration plant.

This biomass plant includes a substantial amount of conditioning equipment for the synthetic gas (syn gas) created by the gasifier to clean it prior to use in the engine. Alternative systems that use boilers rather than engines may use less conditioning equipment.

Emissions

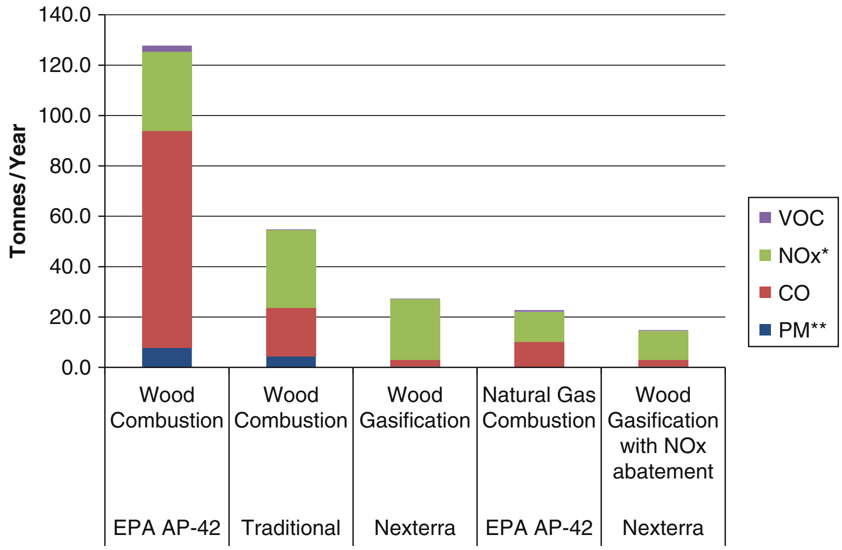
Emissions are of great concern to many biofuel operators as many emissions are regulated by the U.S. Environmental Protection Agency as well as state environmental agencies. Of particular concern are NO_X and particulates generated by combusting fuels. Unfortunately, characterization of emissions from biofuels is not a straightforward process. As stated, the quality and type of biofuels can vary and some equipment may not maintain optimal emissions in part load conditions. As such, emissions monitoring may be required for a period of time by local regulators to verify the installation meets local code. This is especially true in emissions non-attainment zones that provide additional focus on individual pollutants.

Biomass Emissions are of particular concern to regulatory bodies when the boilers are operating in part load conditions. As with any fuel, the temperature at which the fuel burns directly impacts the emissions characteristics. As the temperature decreases, carbon monoxide and particulates are formed. There are a number of ways to treat emissions, which include natural gas–fired afterburners to complete combustion and reduce particulate sizes.

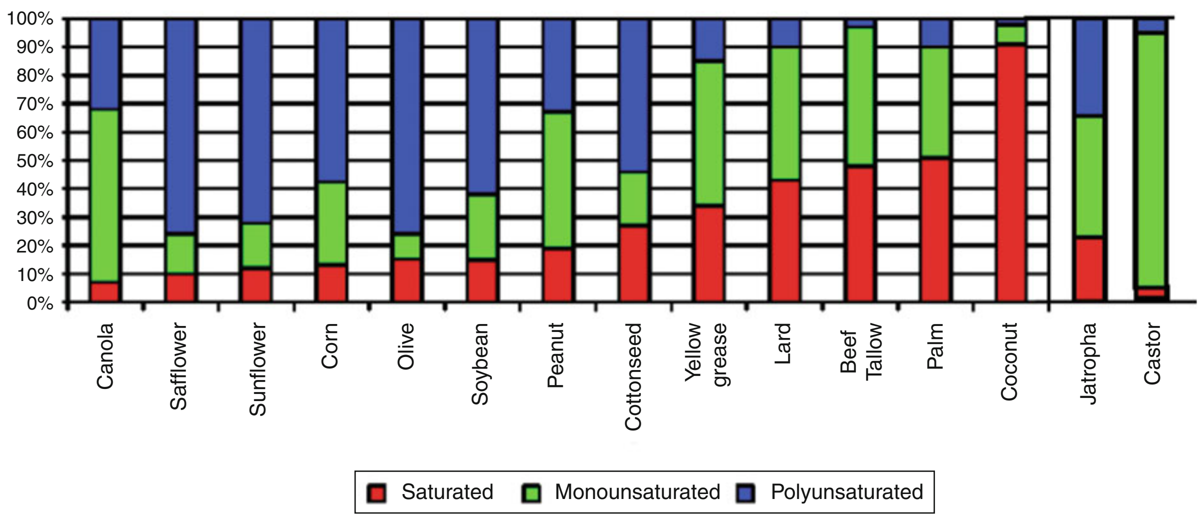
Moisture content is also a large influencing factor in the emissions of biomass. Biomass moisture content below 50% is typically required by most boiler and water heat manufacturers [13, 14]. High moisture content will have the effect of boiling the water inside the fuel. As the water is turned to vapor, it will displace the oxygen in the combustion chamber and reduce the completeness of combustion leading to the creation of carbon monoxide. As a rule, the drier the fuel the better, but also the more expensive the fuel will be. Figure 7 shows a comparison of emissions for wood combustion.

Biodiesel Biodiesel can come from many sources including soybean oil and coconut oil. While the thermodynamic performance of these two biodiesel sources may be similar, their emissions characteristics are quite different. As a rule of thumb, soy-based biodiesel, which is the most common biodiesel source in North America, creates 5–10% more NO_X per kWh than diesel fuel. The emissions characteristics of the biodiesel are dependent on the molecular makeup of the original oil, especially polyunsaturated fat content. Soybean oil has a lot of polyunsaturated fat, as shown in Fig. 8, which indicates that the molecular structure has a lot of double bonds [15].

The consequence of double bonds is that the freezing point is low, which is good, but the cetane number is also low and somewhat unstable in an oxygen environment resulting in increased NO_X emissions [16–19]. Coconut oil on the other hand has very few polyunsaturated fats and a lot of saturated fats. Therefore, coconut oil–based biodiesel has a high freezing point, a high



Biofuels and Sustainable Buildings. Figure 7
Comparison of wood combustion systems [5]

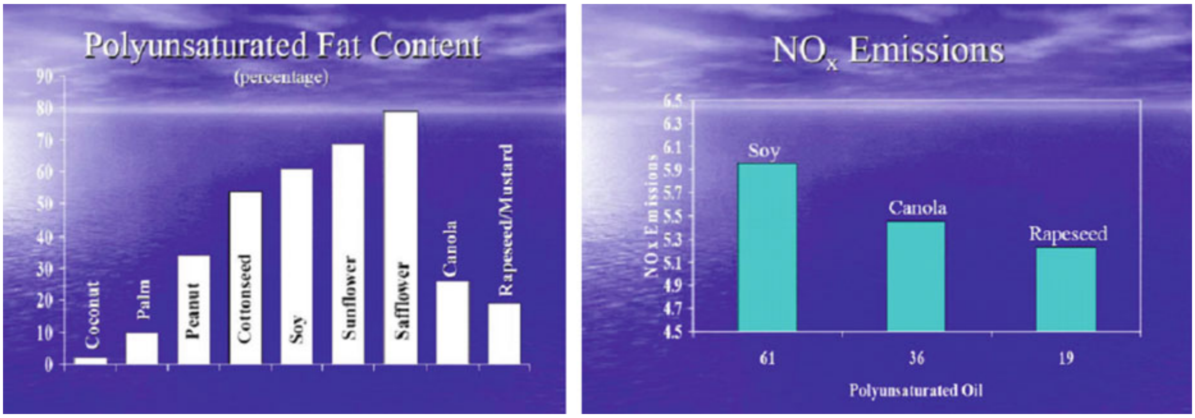


Biofuels and Sustainable Buildings. Figure 8
Average chemical makeup of oils [15]

cetane number, is stable in oxygen environments, and has reduced NO_X emissions as shown in Figs. 9 and 10 [16–19].

As the emissions characteristics change per fuel type and content, and the status of pollutants changes per location; the design team must correlate local environmental regulations with available fuel supply to find the right match.

Carbon Neutrality of Biofuels Biofuels in and of themselves are carbon neutral because burning a certain mass of wood to generate heat will release



Biofuels and Sustainable Buildings. Figure 9
Polyunsaturated fat content of oils versus NO_X emissions [16]

Fuel Property	Saturated 0 double bonds	Monounsaturated 1 double bond	Polyunsaturated multiple double bonds
Freezing Point	High (–)	Medium	Low (+)
Cetane Number	High (+)	Medium	Low (–)
Oxidative Stability	High (+)	Medium	Low (–)
NOx Emissions	Reduction (+)	Medium Increase	Large Increase (–)

Biofuels and Sustainable Buildings. Figure 10
Fuel properties versus chemical makeup [17–19]

a certain mass of carbon dioxide into the air, which will then be absorbed by another tree to grow approximately the same mass of wood. This cycle is what is typically considered when calculating carbon neutrality and set in comparison to fossil fuels emissions.

However, these calculations often do not include the carbon emissions that are generated during farming, harvesting, refining, and distributing biofuels or fossil fuels. Completing a detailed life cycle analysis to determine precisely how much CO_2 is generated from a fuel can be challenging.

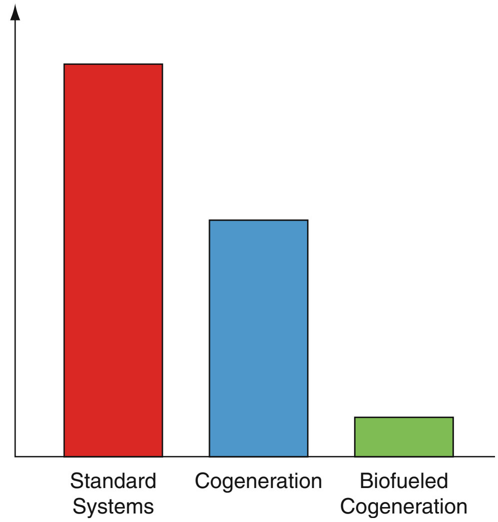
In general, the savings shown in Fig. 11 can be used to estimate savings of cogeneration and biofueled cogeneration versus standard heat and power generation.

Common sense can go a long way in determining the carbon impact of the harvesting, refining, and distribution of a biofuel for a building or campus. If wood pellets are made from waste wood from a nearby lumber mill, then the building owner can be reasonably certain that the CO_2 generated by collecting the waste wood, processing it into pellets, and shipping it the site are relatively small as compared to the boiler emissions.

However, if the biofuel must travel a large distance by truck, in an attempt to offset natural gas delivered via pipeline, then the owner may want to attempt a life cycle analysis. There are a number of sources that specify how much CO_2 is produced per mile traveled, or per unit energy consumed to assist in calculating a rough life cycle analysis [20–22].

Operating Costs

One of the largest pillars of sustainability is operational cost and operational performance. For owners and



Biofuels and Sustainable Buildings. Figure 11
CO_2 generation of standard systems and cogeneration

operators to be able to maintain effective operation of any system and their business, the following principles are good practices to avoid major cost fluctuations.

Buy Local First, pick the biofuel based on local availability. The distribution infrastructure for many biofuels is still weak, so most biofuels are shipped by truck. A closer supply chain is a great asset, and may give the owner some influence over regulation and pricing with the local government.

Quantify Supply Running out of the desired biofuel is a real concern in many parts of the USA, so it is important to identify multiple suppliers of the desired fuel. It is also important to understand the fuel supplier's supply chain and determine their vulnerabilities. Good things to look out for are large potential biomass sources such as lumber mills, nearby biofuel refineries, and landfills or wastewater treatment facilities. These fuel sources represent significant infrastructural investments and are unlikely to shut down rapidly.

Understand Competition The feedstock cost is the single largest influencing factor in the final cost of the refined biofuel. In 2008, the price of many food crops increased dramatically due to increased worldwide food demand and use of food crops for energy. Similarly, a demand for waste fryer oil changed the way restaurants and cafeterias view this waste stream. Several years ago restaurants had to pay to remove waste grease, then they were able to give it away to ambitious "do it yourself refiners," and now there is a commodity value to waste grease in some markets where refiners are purchasing the waste grease from restaurants. Identifying potential competition for the biofuel feedstock may alleviate future cost spikes.

Fuel Flexibility Fuel flexibility is the other option to reduce long-term fuel costs. The best example of this concept is the flex fuel engines that run on E85. The E85 engine can run on any ratio of gasoline and ethanol below 85% ethanol. In other words, the fuel tank can be filled with E85 one day, and regular gasoline the next day as desired. Most gas turbines or engines that can run on biogas can also run on natural gas. The same is true for Diesel engines with respect to biodiesel and Diesel fuel. Some boilers can be co-fired natural gas and biomass, but this should be coordinated with the manufacturer.

Fuel flexibility is important in case there is a supply interruption, such as a reduced availability of biomass for the biogas digester, or a scheduled shutdown by lumber mill, or an equipment failure at the refinery. Suppliers may have contingencies in place to provide a supply during shutdowns. Also, building owners/operators may want to include a backup supply that could bridge the gap during outages. The size of the storage is a function of the load and how many days the supply needs to last.

Most fuels are regulated for quality by the American Society for Testing and Materials (ASTM) including ethanol and biodiesel [23–26]. Biogas must meet the local gas company's standards if it is to enter the natural gas network. Similarly, the biomass must meet the boiler manufacturer's standards in order to not void the warranty.

Future Directions

The technology to effectively employ biofuels into mainstream operation exists and has been effectively demonstrated throughout the USA and the world. Significant improvement needs to be made in the area of documentation and education of engineers, owners, operators, and code officials. Like any other industry, this will happen over time as owners request biofueled systems as an alternate to fossil-fueled systems. Owners and governments need to be willing to send their operators and code writers for training to assist in the adoption of these technologies. As owners increasingly demand biofueled systems, building designers, engineers, and the associated services will follow suit to meet demand.

The largest hurdle for the successful long-term operation of biofuels is understanding the minor differences between fossil fuel systems and biofuel systems. Often building operators will fail to see the subtle difference between the systems that can cause unnecessary problems or failures in long-term operation, and cast doubt on the biofuel industry or a particular technology. As the body of knowledge and experience grows, installers and operators will learn to benefit from the advantages of biofuels and avoid the potential pitfalls to make biofuels as common a part of building operations as fossil fuels are today.

Outside of building operations, continued improvement in supply chain management to keep costs under control will be the largest deciding factor for the long-term success of biofuels. A great deal of research is being conducted to replace the use of food crops as a biofuel feedstock with nonfood alternatives such as wood chips, grass clippings, algae, and other biomass residue as well as increasing the efficiency of refining biofuels.

Biofuels will solve some of the pollution problems faced by the building industry today as well as help diversify the energy portfolio to enhance price stability and energy security. Biofuels along with cogeneration systems will become increasingly attractive as fossil fuels become costlier and environmentally riskier to extract over time. However, biofuels are a commercial commodity and as such will be subject to market forces and the laws of supply and demand. The same price fluctuations that effect transportation fuels today are already starting to affect the biofuel market as demand increases. Owners and operators will need to be aware of where their biofuel comes from as the impacts may be felt more acutely by a local population as opposed to fuels that come from the other side of the world.

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Daylight, Indoor Illumination, and Human Behavior

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Article Outline

Glossary

BTDF The bidirectional transmission distribution function. The BTDF characterizes the distribution in luminous output across the full hemisphere of transmitted rays and usually needs to be determined for every incident direction. It is needed to simulate the performance of complex glazing materials and systems.

Climate-based daylight modeling The prediction of various radiant or luminous quantities (e.g., irradiance, illuminance, radiance, and luminance) using sun and sky conditions that are derived from standardized annual meteorological datasets.

Daylight The totality of visible radiation originating from both the sun and the sky.

Daylight factor The ratio of internal illuminance to unobstructed external illuminance under the CIE standard overcast sky.

Daylight metric Some mathematical combination of (potentially disparate) measurements and/or dimensions and/or conditions of daylight represented on a continuous scale.

Illuminance The total luminous flux incident on a surface per unit area. It is a measure of the intensity of the incident light, wavelength-weighted by the eye's sensitivity to correlate with human brightness perception. SI unit: lux or lumens per square meter.

Luminance Photometric measure of the luminous intensity per unit area of light traveling in a given direction. It describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle. The SI unit for luminance is candela per square meter.

Definition of the Subject

Daylight in buildings is the natural illumination experienced by the occupants of any man-made construction with openings to the outside, e.g., dwelling and workplace. The quantity and quality of daylight in buildings is continually varying due to the natural changes in sun and sky conditions from one moment to the next. These changes have components that are random (e.g., individual cloud formations), daily (i.e., progression from day to night), and seasonal (e.g., changing day length and prevailing weather patterns). For any given sky and sun condition the quantity and character of daylight in a space will depend on the size, orientation, and nature of the building apertures; the shape and aspect of the building and its surroundings; and the optical (i.e., reflective and transmissive) properties of all the surfaces comprising the building and its surroundings.

The purpose of the very earliest shelters – the forerunners of buildings – was to protect from the elements. The first buildings to include deliberate elements of daylighting design were often places of worship, many of which survive to this day. Only when glass became relatively commonplace in the seventeenth century did the provision of daylight for everyday buildings become a consideration. Window design was invariably tailored to the prevailing climate, e.g., small with deep reveals for locales where the solar component of daylight needed to be controlled to prevent overheating. As the cities of the industrialized

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world became more populous, building densities increased and the provision of daylight for buildings became a planning issue. This eventually resulted in the formulation of the daylight factor which was intended to be a measure of the daylighting potential of a building, and which could be predicted at the design stage using a variety of methods. Devised in the first half of the twentieth century, the daylight factor still forms the basis of many guidelines and recommendations for building design, notwithstanding the fact that a daylight factor value is, by definition, completely insensitive to the building orientation and any consideration of climate.

Advances in glass making and window technology allowed architects to design buildings where the perimeter wall could be almost entirely glazed. Commercial buildings in particular became larger with deeper plan designs so that, despite the highly transparent facade, many occupants were situated far from the windows and so received little daylight. As conspicuous icons symbolizing modernity and prosperity, these designs became the exemplars for architects all over the world, and now many cities feature highly glazed buildings regardless of the local climatic conditions. Thus the daylighting characteristics of office buildings in particular tended to be dictated by considerations of architectural style rather than climate-adapted design. These trends were not hindered by the continued reliance on the daylight factor as an evaluative scheme since the measure is itself climate and orientation insensitive.

For the majority of buildings, it is incumbent on the occupants to moderate the internal daylight conditions using some form of blinds or shades. Occupants will deploy blinds/shades in an effort to moderate the internal environment according to their perceptions of both visual discomfort (e.g., daylight glare) and thermal discomfort (e.g., to avoid direct sun) which vary greatly from person to person. Also, once deployed, blinds/shades will tend to remain closed long after the external condition has passed. Thus it is common to see blinds closed for much of the occupied time. Consequently, the potential to exploit daylighting is often not realized because the blinds are left closed most of the time and the electric lights are left switched on.

Toward the end of 1990s, the daylighting of buildings began to achieve greater attention for a number of reasons. The two most important drivers were:

1. The widespread belief that the potential to save energy through effective daylighting was greatly underexploited.
2. The emergence of data suggesting that daylight exposure has many positive productivity, health, and well-being outcomes for building occupants.

The first of these concerns originated in the 1970s following the energy crisis and culminated with the widely accepted need to reduce carbon emissions from buildings in order to minimize the anticipated degree of anthropogenic climate change. This in turn led in the 1990s to the formulation of guides and recommendations to encourage the design and construction of low-energy buildings and also for the retrofit of existing buildings. All these guides contain recommendations on daylighting, invariably founded on the daylight factor or an equally simplistic schema such as glazing factors. The productivity, health, and well-being effects related to daylight exposure are not yet fully understood, and it is not yet known what the preferred exposure levels should be nor if existing guidelines would be effective for these quantities.

Almost concurrent with the emergence of the two key drivers noted above were a major advancement in the way daylight in buildings could be modeled and the development of numerous new glazing systems and materials to better exploit daylighting in buildings. These developments are expected to lead to significant changes in the way that daylight in buildings is both evaluated (through modeling) and exploited (by new glazing systems and materials).

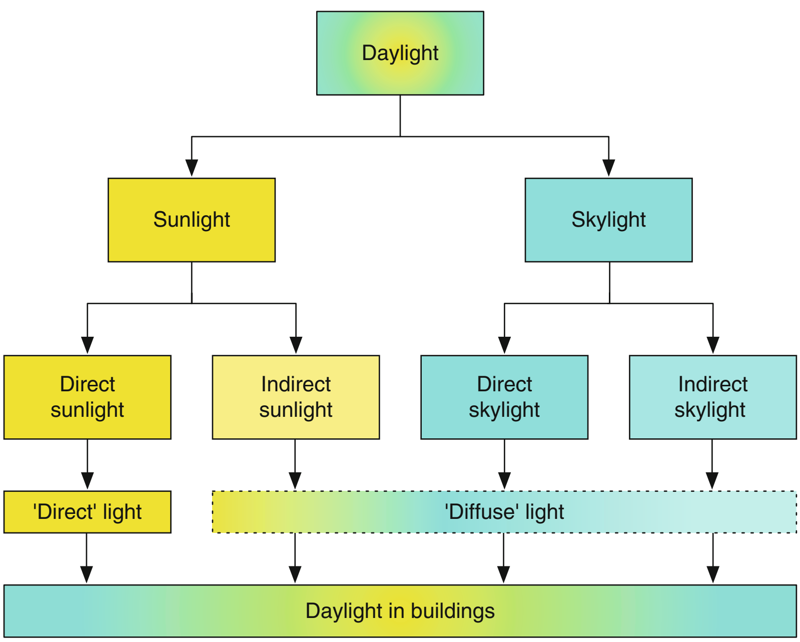
Introduction

Daylight is generally taken to be the totality of visible radiation originating from the sky and, when visible, the sun during the hours of daytime. The source of all daylight is in fact the sun. Scattering of sunlight in the atmosphere by air, water droplets, and dust gives the sky the appearance of a self-luminous hemispherical source of light. Sunlight is commonly referred to as direct light since it appears to originate from a small source and can be highly luminous casting sharp shadows. The sky, however, is an extended source of illumination that casts only soft shadows and so skylight is commonly referred to as diffuse light. In building science, diffuse light includes also light from the sky and/or the sun that has undergone one or more reflections from surfaces that are generally not mirrorlike in character.

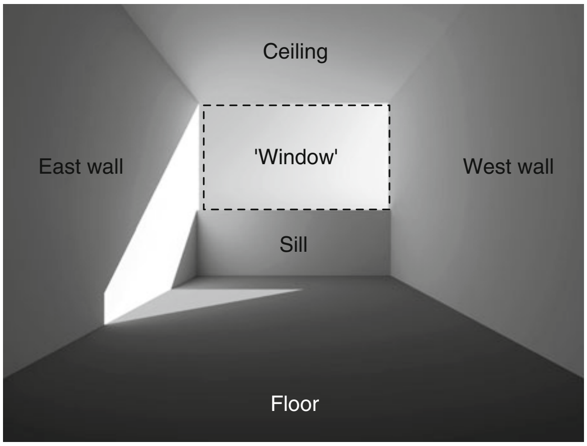
Daylight may arrive at a point inside a building either directly or indirectly from the luminous source, i.e., from the sun or from the sky. Direct illumination generally results from having an unobstructed view of the source. Indirect illumination is when the light arrives at the point following one or more reflections. Thus, strictly speaking, there are direct and indirect components of illumination from both the sun and the sky (Fig. 1). Although the sun and the sky are both luminous sources, direct sunlight when present is given special consideration because of the small angular size of the sun and its potentially large contribution to illumination (and also its heating effect). Thus illumination from direct sunlight is commonly referred to as "direct light." In contrast, light from the sky – arriving either directly or indirectly – is commonly referred to as "diffuse light." Sunlight that has undergone one or more diffuse reflections is also commonly referred to as "diffuse light." Note that the mode of reflection of the direct sunlight is important: a specular (or "mirror") reflection of sunlight will produce a *redirected* beam of direct light rather than diffuse light. For reflections (and transmissions) that are part-specular and part-diffuse, the distinction between direct and diffuse light can become lost. Reflections can occur either internal or external to the building space under consideration.

Components of Daylight Illumination Indoors

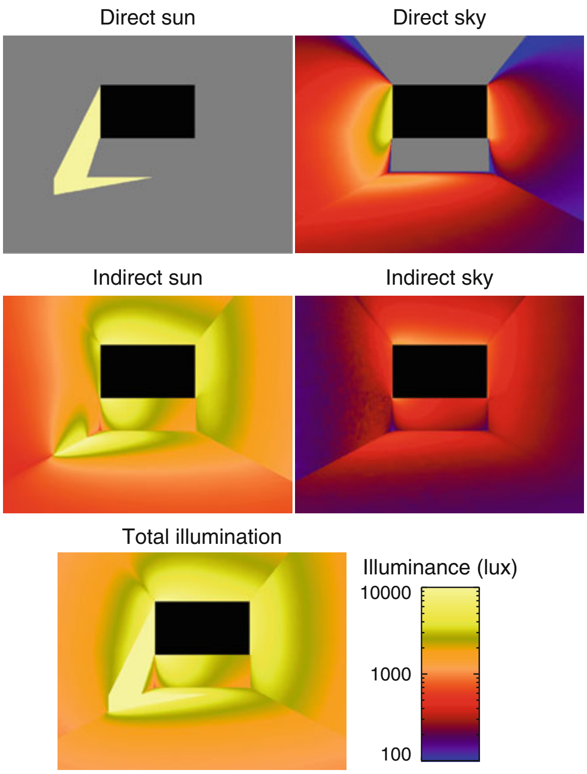
The image shown in Fig. 2 is a simulation of the daylight distribution in a simple space under clear sky conditions. The viewpoint of the virtual camera is "looking" toward the south-facing window. The external conditions are those of a clear sky with sun, with the sun 30° west (i.e., to the right) of the view direction, and at an altitude of 45°. The direct sun illumination on the east wall and the floor is clearly visible. The space



Daylight, Indoor Illumination, and Human Behavior. Figure 1
Components of daylight illumination in buildings



Daylight, Indoor Illumination, and Human Behavior. Figure 2
Simulated image of a simple space illuminated by sunny clear sky conditions



Daylight, Indoor Illumination, and Human Behavior. Figure 3
Components of illumination for the simple space shown in Fig. 2

is 3.0 m wide, 9 m deep and 2.7 m high and it "sits" on a ground plane that is 100 m^2. The reflectance values assigned to the surfaces are typical of those commonly used for office buildings and the external ground plane. No glazing was used in the window aperture to eliminate potentially distracting reflection patterns for the example that follows. The simulation of the space was actually carried out in stages so that the individual components of illumination described above could be computed and shown individually. The image in Fig. 2 shows how the space might appear to the eye, in other words it is a representation of the predicted surface brightness (or luminance) of the scene. The light that is incident on a surface is termed the illuminance and is a measure of the illumination (i.e., the light arriving) at a particular point – this is what we would measure with a light or lux meter. The images in Fig. 3 show the distribution and relative proportions of the four components of daylight as illuminance values, together with a fifth image that shows the total illuminance (i.e., the sum of the four components). The magnitude of the illuminance is shown using color and the relation between the two can be read from the legend. Note that a logarithmic scale is used that covers the range from 100 to 10,000 lux. Areas where the illuminance value was zero are shaded gray and the window aperture has been shaded black.

Direct Components The direct sun image shows the pattern of sun illumination on the East wall and the floor. The illuminance value on the wall is around 40,000 lux (values higher than the legend maximum of 10,000 lux will all have the same shade). Because the scene contains no obstructions, all of the surfaces visible in the image except the ceiling and the sill (Fig. 2) have a direct "view" of the sky and so they receive some illumination directly from the sky. The amount of illumination received at a point depends on:

- The angular size of the patch of sky "seen" through the window (from that point)
- The brightness (i.e., luminance) of the patch of sky
- The transmission properties of the glazing (not used for this illustration)

The areas of wall nearest to the window have the best view of the sky, and they receive the largest illumination. Note that the illuminance is greater on the East wall because this side "sees" the circumsolar region, i.e., the locus for the sun position and therefore the brightest part of the hemispherical clear sky pattern. The illuminance toward the back of the space (away from the window) reduces gradually as the apparent size of the window diminishes. The illuminance at the highest part of the walls drops off rapidly (i.e., blue shade) as the view of the sky reduces to zero.

Indirect Components The indirect components of illumination show the illuminance that results from multiple light reflections. These reflections usually introduce light from the external environment and also redistribute light within the space. The degree to which this occurs depends on the quantity of incident light (i.e., the direct components) and the reflective properties of the various surfaces. The images showing the indirect components do not include the direct component. The pattern of indirect sun illumination in Fig. 3 is quite complex, but it can be understood with reference to the direct sun pattern. The illuminance resulting from the first reflection of light will generally have the greatest contribution to the indirect component since the intensity of light diminishes with each subsequent reflection. Thus those areas of floor, wall, and ceiling that have the best "view" of the directly illuminated surfaces (inside and out) will have the highest indirect sun illuminance. The west wall "sees" the brightly illuminated sun patch on the east wall (together with the smaller sun patch on the floor) and so it receives a marked quantity of indirect (sun) illumination. For any given size of directly illuminated sun patch, the indirect illumination effect from one on the floor will be less than from one on the wall because the floor has a lower reflectivity. The ceiling will receive indirect sun light from both the sun patches inside the space and the sun-illuminated ground outside. Subsequent reflections will serve to redistribute this, but the bulk of the indirect sun illumination will be at the window end of the space, as is evident in Fig. 3. The indirect component of illuminance from the bulk of the indirect sun illumination will be at the window end of the space, as is evident in Fig. 3. The indirect component of illuminance from the sky shows a gradual diminution going away from the window and toward the back of the space. The slight asymmetry in illumination between the walls can be explained because, at the first reflection, the west wall "sees" the brighter east wall.

This illustration shows how complex the quantity, quality (i.e., direct, diffuse, etc.), and the patterns of natural illumination can be for even the simplest of indoor spaces under naturally occurring daylight conditions. For more realistic spaces, the patterns of illumination will be more complex and, of course, continually changing throughout the day/year.

Buildings and Daylight

The earliest windows were simply holes in the wall or roof of a building. They were providers of daylight and also ventilation, but could be covered with animal hide, cloth, or wood to protect the building occupants from the elements. Daylight would almost always be desirable inside the building, whereas ingress of cold air and rain would generally be avoided. The need for a light transmitting medium that would protect from the elements was first met by translucent materials such as flattened hides and thinly sliced sheets of marble. It was with the invention of glass that the story of daylighting design for buildings truly began.

The first recorded use of glass for windows was not until approximately 100 AD by the Romans. The largest panes that could be manufactured were fairly small. The use of vertical and horizontal dividers – called, respectively, mullions and transoms – increased the size of areas that could be glazed since small pieces of glass could be combined to create large windows. Substantial dividers could additionally form part of the load-bearing structure.

The Industrial Era: 1700s to the Present Day

Glass windows became common in homes in the most developed parts of Europe only in the early seventeenth century. With the advent of improved production techniques in the following century, the cost of glass became less of a limiting factor in its use, though its relative cost compared to other building components was still fairly high. Notwithstanding the high cost of glass, the real cost of artificial light (i.e., as a proportion of the overall household expenditure) was several thousand times what it is today on a per lumen of light basis [1].

The majority of building spaces were side-lit by vertical windows, though the size and arrangement of the windows depended on a number of factors, e.g., intended use, aspect and grandeur or otherwise of the property. Whatever the function or style of the building, window design was, with varying degrees, adapted to the local climatic conditions. Regardless of the size of the window, there would always be a trade-off between daylight provision, heat loss, and solar gain. Internal shutters, often in conjunction with curtains, tended to be used in colder climates where buildings were heated much of the year and heat loss through the windows was significant. In hotter climates where heating was rarely needed, overheating due to undue solar ingress was common in the summer months. Solar gain was moderated by having external shutters which could be closed to cover most or all of the window. Shutters usually had fixed or variable slats that were principally to allow ventilation but also some diffuse light, Fig. 4. Global warming has led to considerations that southern European architectural features such as external shutters may become commonplace in more northerly latitudes in the next 20–50 years.

Rooflights Rooflights began to appear in the mid 1700s when advances in the manufacturing process allowed the fabrication of large sheets of glass at a relatively low cost. Rooflights became a common feature in ordinary houses in the late nineteenth century when mass-produced rooflights with cast iron frames became available. By the late nineteenth century, glass had become relatively inexpensive and was available in good-quality large sheets. Factory buildings since the late 1800s were often designed to provide high levels of natural illumination evenly distributed across the workspace – a goal which is relatively easily achieved in single-story top-lit buildings. The potential for daylighting modern large-span buildings (e.g., storage facilities) was generally underexploited, but energy concerns have led to a rediscovery of this resource.

In domestic buildings, rooflights are now more common and more popular than ever before, particularly in attic conversions and in refurbished historic buildings. In newly designed dwellings, the rooflight is often seen as an integral feature of the daylighting design, and automated opening and blinds operation allows for high-level placement that would have been

Daylight, Indoor Illumination, and Human Behavior. Figure 4
Solar protection using moveable shutters (Dordorgne region, France)

Daylight, Indoor Illumination, and Human Behavior. Figure 5
Rooflights in a modern dwelling (Photo courtesy VELUX A/S)

impractical only 10 years ago, Fig. 5. Depending on the function and occupancy of the space, domestic rooflights can result in significant lighting energy savings [2].

Daylighting in Special-Purpose Buildings

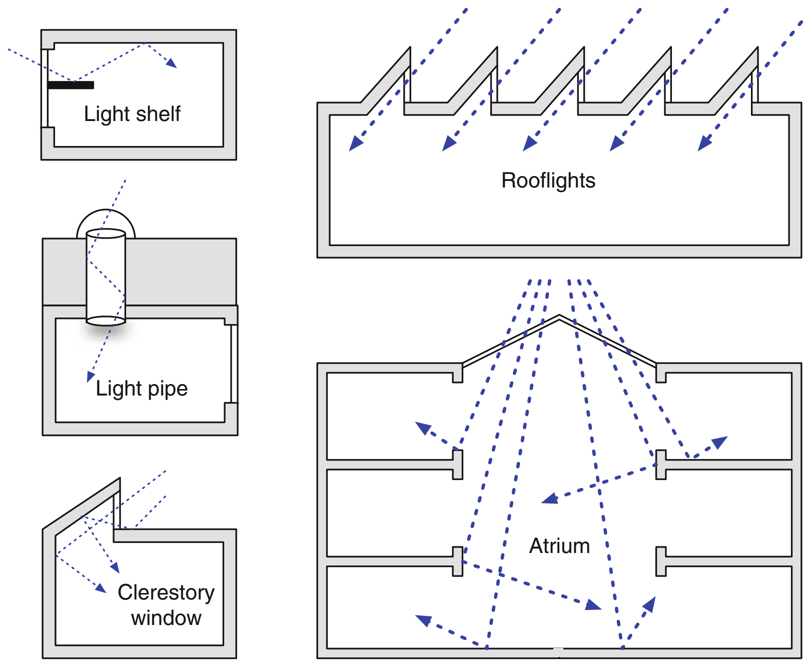
Buildings such as art galleries and museums typically have special requirements for daylighting. Current display practice for highly light-sensitive objects is usually to exclude daylight and use subdued levels of electric lighting commensurate with recommendations for total annual exposure to illumination published by professional bodies and, in some countries, included in legislation. In the wider historical context, this is a relatively recent development since before the 1960s the use and control of light was largely an issue of household practice and museums were usually designed to maximize their use of available daylight through large areas of glazing. From the 1960s onward, daylight has been largely excluded from museum galleries with the exception of those used for art collections (particularly oil paintings) and historic interiors, where its exclusion was felt deleterious to the interpretation of the ensemble of interior and contents. While this move has been partially reversed, with designers expending a great deal of ingenuity trying to blend daylight with new designs of displays and galleries, the success of their work has been variable. In part this is related to our poor understanding of daylight's quantitative performance and the extremely limited techniques, most of them unchanged over half a century, by which daylight in interiors is predicted (see section "The Daylight Factor"). Daylighting design for museums remains one of the more challenging areas of architectural endeavor.

Daylighting Strategies

A daylighting strategy is any building feature that is intended to increase, enhance, or moderate the daylight entering a building. The term is not generally used to describe the typical vertical window with ordinary glazing, though readers may see it used in that way. The strategies can be loosely divided into those that:

1. Employ orthodox construction methods but the building apertures and windows use configurations other than the typical vertical perimeter arrangement
2. Make use of recent and emerging technologies to moderate and/or control the daylight

The first of these, what might be called basic daylighting strategies, are described in this section. The others are described in a later section "Advanced Glazing Systems and Materials". The basic daylighting strategies are essentially building configurations that depart from the norm of vertical glazing; however, they also include, e.g., simple exaggerations of standard building features such as the window reveal to improve the self-shading properties of the window. The various strategies do not occupy distinct categories and many designs feature elements of two or more. There are



Daylight, Indoor Illumination, and Human Behavior. Figure 6
Daylighting strategies

a number of basic daylighting strategies that are commonly used in buildings. A few of the more common ones are illustrated in Fig. 6.

A light-shelf is any horizontal overhang which abuts and divides a vertical window. The upper and lower surfaces of the shelf are usually highly reflective, e.g., painted bright white, though the upper surface may have a mirror finish. The purpose of the light-shelf may be twofold: (a) to redirect daylight deeper into the space through multiple reflections and (b) to offer partial shading from direct sun for those occupants close to the light-shelf.

The clerestory is any window above eye-level height that allows light to penetrate deep into a space. Strictly speaking, the clerestory window in modern buildings is a distinct window aperture, so the upper part of a tall window separated by frame bars would not normally be described as a clerestory window. The effectiveness of a clerestory window for deep penetration of daylight generally improves with increased height of the window. Clerestory windows can feature on the perimeter facade, often above standard height glazing, or further back in the space to better illuminate those areas farthest from the main windows (Fig. 6).

A light-well is a shaft within a building that is open to the outside at the top to admit daylight. The sides of the light-well usually have a bright finish to encourage reflection of light deep into the well. Windows open onto the shaft to admit daylight to spaces that otherwise do not have any direct access to daylight. The level of daylight that a light-well provides to adjacent spaces tends to be fairly small and decreases rapidly away from the opening. The light-well may also serve as a means to encourage natural ventilation for those spaces deep in the core of the building. Where the primary function is ventilation, the structure is usually referred to as an air-shaft. Light-wells and air-shafts were a common feature in early-twentieth-century tenement buildings where the high density placed restrictions on the availability of natural light and air to core spaces.

The light-pipe, also known as light-tube or more generally as a tubular daylight guidance system (TDGS), is an evolution of the light-well design where a conduit transports light through multiple reflections (Fig. 6).

Daylight, Indoor Illumination, and Human Behavior. Figure 7
Typical light-pipe diffuser designed to appear like a luminaire. Note that the nearby luminaire is daylight sensing and switched off due to the daylight illumination provided by the light-pipe

A light-pipe is usually comprised of the collector at one end and the diffuser at the other, Fig. 7. The inside surface of the pipe usually has a metallic/mirror finish with a high reflectivity. Light-pipes can be made to almost any dimensions, though most are circular in cross section and less than 1 m in diameter, and they can be either straight or have minor bends. Light loss in bends will be higher than for the equivalent length of straight pipe, and so are avoided wherever possible. The efficiency of a light-pipe is the ratio of the lumens delivered into the room by the diffuser to the lumens received by the collector, expressed as a percentage [3]. The efficiency decreases with length of the tube, and so light-pipes are rarely longer than 5 m in length. In office buildings, the use of light-pipes is usually restricted to the topmost story, though they may occasionally be used to convey daylight to the next floor below also. For domestic dwellings, they are most commonly used to supply daylight to central areas such as upper-story stairwells that do not receive any light from perimeter windows. Thus the length of the pipe is governed by the distance traversed through the attic space between the ceiling diffuser and the collector on the roof.

Opened in 1993, the Queens Building at De Montfort University (Leicester, UK) is an award-winning low-energy design that incorporates a number of daylighting strategies. The core of the building is illuminated by several rooflights (which double as ventilation openings) and also "borrowed" light from well-daylit adjacent spaces, Fig. 8. The vertical facades on an enclosed courtyard area between two projecting wings have a high reflectivity finish to enhance the inter-reflected component of light that enters the windows, thus ameliorating to a degree the shading effect of the opposing obstructions, Fig. 9. Daylight penetration is encouraged by the use of high-level windows in combination with high ceilings, and a degree of solar protection is provided by having tall narrow windows set in deep reveals, Fig. 10.

The Decline of Climate-Adapted Building Design

Prior to the 1900s, buildings generally incorporated features that evolved from the need to temper the internal conditions in response to the prevailing climate for that locale. In hot climates with a high

Daylight, Indoor Illumination, and Human Behavior. Figure 8
Rooflights and glazing apertures to allow for light "spillage" from adjacent spaces

Daylight, Indoor Illumination, and Human Behavior. Figure 9
Highly reflective courtyard

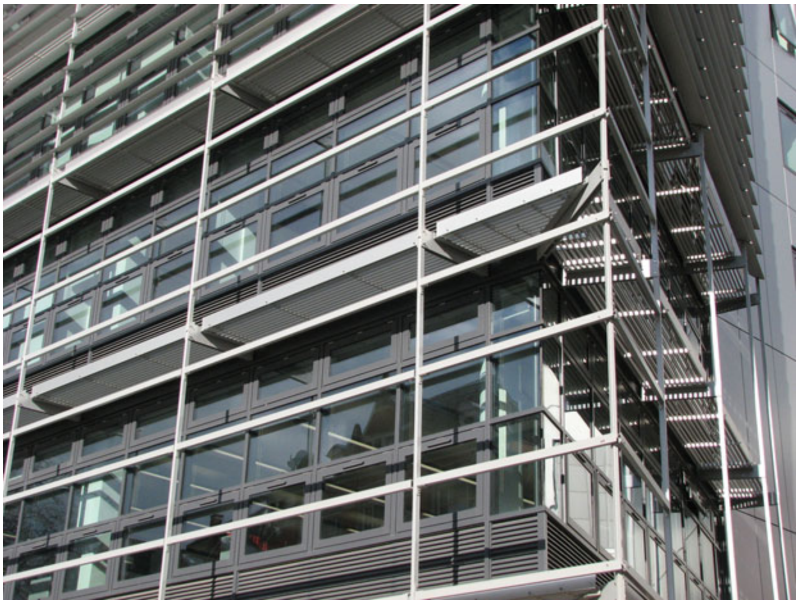
propensity for sunshine, buildings would be designed to include elements of solar control either by passive or active means. For example, on sun-exposed facades there would be small windows set in deep reveals to provide self-shading (passive control) or perhaps larger windows with moveable shutters (active control). In less hot/sunny climates, window apertures would tend to be larger and solar control less of an issue – though

Daylight, Indoor Illumination, and Human Behavior. Figure 10
High-level glazing and deep window reveals

there would be other concerns such as heat loss. Thus, all buildings contained to varying degrees features in their design that were climate-adapted, and which, over time, became an intrinsic part of that locale's vernacular architecture.

The latter half of the twentieth century witnessed a globalization in architectural form. The highly glazed office tower became the most conspicuous symbol of industrial progress, and hence an inspiration for architects and designers worldwide – regardless of their local climatic conditions. Designers typically rationalized the use of large glazing areas in terms of their daylight provision, but often it was more likely the pursuit of style. Aside perhaps from the possibility of a view to the outside, the daylighting benefit to the majority of occupants in a deep plan space was not great since very few would be close enough to the perimeter to gain any direct benefit in terms of daylight provision. Furthermore, the daylighting potential of highly glazed buildings was often not realized because the manually operated shades/blinds needed to control direct sun were typically left closed long after the external condition had changed. This is the case in fairly temperate climates such as the UK and Northern Europe, but the situation is worse still in sunnier locals. While internal shades do provide occupants with immediate protection from direct sun, they generally have only a limited overall heat rejection effect. Thus, solar radiation, once it has passed through glazing, will inject heat energy to the space which may need to be removed by active cooling (e.g., air-conditioning) if it causes overheating. The almost completely glazed building shown in Fig. 11 exemplifies the total abandonment of climate-adapted design in favor of architectural style. Solar gain will occur across the entire glazed area, and, since the internal shades are dark, virtually all of that solar gain will be instantly reprocessed into heat energy. Thus it is likely that the building will require air-conditioning throughout summer and also at spring/autumn times of the year whenever there is sun. The non-shaded glazed area (i.e., that which could provide daylight but not permanently covered by blinds) occupies approximately one fifth of the total glazed area. Compare that modern design, a tourist office in the Dordogne region, with the climate-adapted traditional design from the same locale shown in Fig. 4. A common practice with highly glazed buildings is to shield the exposed facades

Daylight, Indoor Illumination, and Human Behavior. Figure 11
An almost completely glazed building (tourist office) in the Dordorgne region, France



Daylight, Indoor Illumination, and Human Behavior. Figure 12
Solar protection provided by a brise-soleil, Hugh Aston Building, Leicester, UK

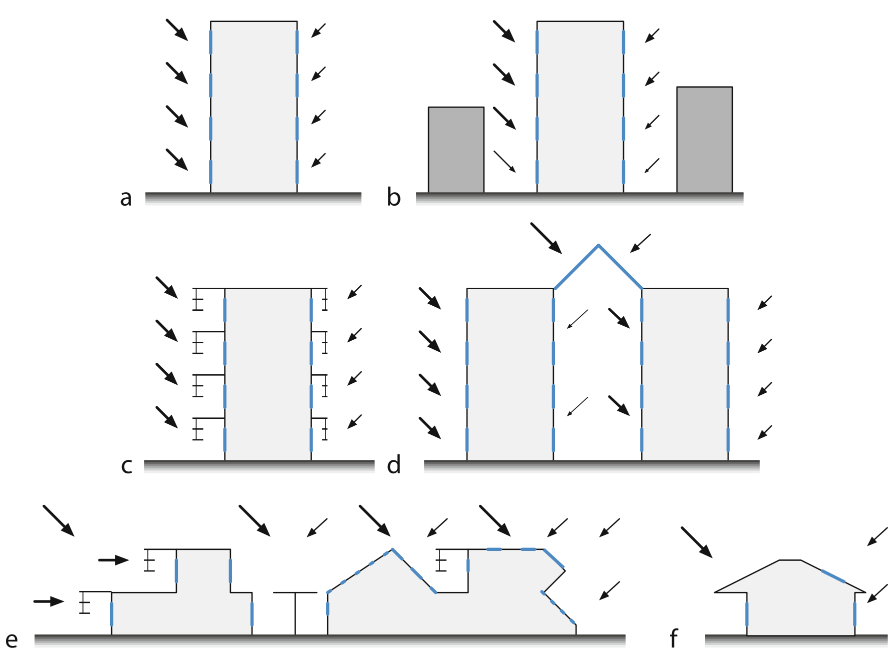
with a permanent structure known as a “brise-soleil” (from the French meaning “sun breaker”), Fig. 12. A brise-soleil can be almost any design providing that it offers some degree of solar protection. However, it is true that typical usage of brise-soleil is also more the product of architectural style than resulting from precise performance evaluation of their shading efficiency.

The "Well-Tempered" Daylit Environment

A "well-tempered" daylit environment is one where the fixed (i.e., static) architectural form provides both good daylighting and effective solar protection. Thus minimizing – though in practice rarely eliminating – the need for occupants to operate blinds/shades.

The potential for the fixed form to temper the daylighting of the space depends on the building type, specifically on the richness/variety of the architectural form. This is illustrated by the schematic showing various building types given in Fig. 13. The weight of the arrows is used to indicate the degree of exposure to daylight, i.e., from both the sun and the sky. For the typical rectangular office building (in the northern hemisphere) the south-facing facade will be exposed to direct sun (Fig. 13a). For this type of building the scope to temper the daylit environment is limited to the manipulation of a few basic building parameters, e.g., glazing ratio, transmissivity, etc. Optimization of these will have some beneficial effect, but the occupants with a south-facing window will have to resort to frequent use of the blinds/shades to moderate the internal luminous environment. If shaded by a nearby building (Fig. 13b), the daylighting for the south-facing offices could actually be improved if the overshadowing was such that occurrence of direct sun was reduced but the diffuse daylight provision was still adequate. On the north-facing side of the building however, overshadowing could, in the main, lead to a reduced daylighting potential. Other features and design opportunities could serve to improve the daylighting of the space by tempering the direct sun while still admitting sufficient diffuse light. These include brise-soleil (Fig. 13c) and atria (Fig. 13d). The greater the potential for richness/variety in the architectural form, the greater the opportunity for producing a "well-tempered" daylit environment. Low-rise buildings such as schools (Fig. 13e) and also residential buildings (Fig. 13f) offer perhaps the greatest opportunity to realize a "well-tempered" daylit environment since the building mass and the apertures can be designed with the greatest flexibility to control the admittance of direct sun while providing adequate diffuse illumination.

At present, the realization of a "well-tempered" daylit building is more of an art than a science, relying more on



Daylight, Indoor Illumination, and Human Behavior. Figure 13
The "well-tempered" daylit environment

the intuition and insight of the experienced daylight designer than what standard evaluative measures such as the daylight factor (see below) can inform.

Guidelines, Measures, and the Evaluation of Daylighting

Illuminance for Task

The absolute levels of illuminance that are needed for any particular task depend on the visual acuity required for the task and, to a lesser degree, the nature of the environment in which the task is to be carried out. Most developed countries have produced design guides which give recommended illuminance levels depending on task and/or setting. The following is a selection of recommendations produced by the Chartered Institution of Building Services Engineers (CIBSE) [4]:

- 100 lux for interiors used rarely, with visual tasks confined to movement and casual seeing without perception of detail, e.g., corridors, changing rooms, bulk stores, auditoria
- 200 lux for interiors where the visual tasks do not require perception of detail, e.g., foyers and entrances
- 300 lux for interiors where visual tasks are moderately easy, e.g., libraries, sports and assembly halls, teaching spaces, and lecture theaters
- 500 lux for interiors where the visual tasks are moderately difficult and also where color judgment may be required, e.g., general offices, kitchens, laboratories and retail shops
- 1,000 lux for interiors where the visual tasks are very difficult, requiring small details to be perceived, e.g., general inspection, electronic assembly, retouching paintwork, cabinet making, and supermarkets

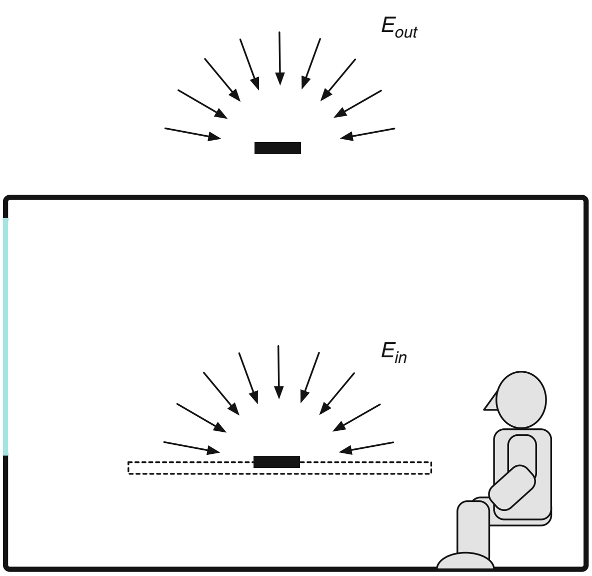
Recommended illumination levels were conceived primarily for the purpose of designing artificial lighting systems and not for the daylighting design of buildings because the variation in the provision of natural daylight is such that it is virtually impossible to deliver specific natural illumination levels without huge fluctuations occurring. For buildings therefore, design guidance was formulated in terms of building properties which are evaluated under a single, static "worst-case" daylight condition: an overcast sky. This is the basis of the daylight factor described in the following section. It is only with recent advances in daylight prediction techniques that absolute levels of daylight illumination under varying sky and sun conditions has become a consideration in the evaluation of the daylighting potential of a building (see section "Climate-Based Daylight Modeling").

The Daylight Factor

Design guidelines worldwide currently recommend daylight provision in terms of the long-established daylight factor (DF) [5]. The daylight factor at a point in an internal space is simply the ratio of internal illuminance E_{in} to unobstructed horizontal illuminance E_{out} under standard CIE overcast sky conditions, Fig. 14. It is usually expressed as a percentage, so there is no consideration of absolute illumination values:

$$DF = \frac{E_{in}}{E_{out}} 100\% \tag{1}$$

The luminance of the CIE standard overcast sky is rotationally symmetrical about the vertical axis, i.e., about the zenith. In other words, the illumination



Daylight, Indoor Illumination, and Human Behavior. Figure 14
The daylight factor is the ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky conditions

that the standard overcast sky delivers to an internal space will be the same regardless of the compass orientation of the building. And, since the sky is fully overcast, there is no sun. Thus for a given building design, the predicted DF is insensitive to either the building orientation (due to the symmetry of the sky) or the intended locale (since it is simply a ratio). Because the sun is not considered, any design strategies dependant on solar angle, solar intensity, redirection of sunlight, etc., can have no influence on the daylight factor value.

The daylight factor was conceived as a means of rating daylighting performance independently of the actually occurring, instantaneous sky conditions. Hence it was defined as ratio. However, the external conditions still need to be defined since the luminance distribution of the sky will influence the value of the ratio. At the time that the daylight factor was first proposed, it was assumed that heavily overcast skies exhibited only moderate variation in brightness across the sky dome, and so they could be considered to be of constant (i.e., uniform) luminance. Measurements, however, revealed that a densely overcast sky exhibits a relative gradation from darker horizon to brighter zenith; this was recorded in 1901. With an improved, more sensitive measuring apparatus, it was shown that the zenith luminance is often three times greater than the horizon luminance [6]. A revised formulation for the luminance pattern of overcast skies was presented by Moon and Spencer in 1942, and it was adopted as a standard by the CIE in 1955. Normalized to the zenith luminance the luminance distribution of the CIE standard overcast it has the form:

$$L_\zeta = \frac{L_z(1 + 2\cos\zeta)}{3} \tag{2}$$

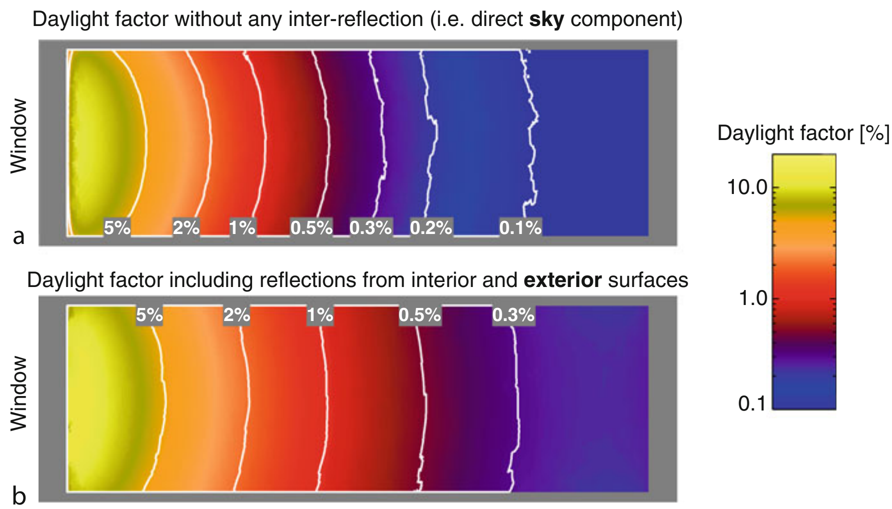
where L_ζ is the luminance at an angle ζ from the zenith and L_z is the zenith luminance. Comparisons with measured data have demonstrated the validity of the CIE standard overcast sky model as a representation of dull sky conditions [7]. Thus, since 1955, the daylight factor is strictly the ratio of internal to external illuminance determined under a sky luminance distribution that conforms to the CIE Standard overcast sky pattern (Eq. 2). Note that in papers and reports published prior to 1955, the "daylight factor" is likely to refer to a ratio determined for an actual or assumed uniform sky luminance pattern.

Influence of Building Properties on the Daylight Factor The daylight factor was intended to be a measure of the daylighting potential of a space. The key building properties that determine the magnitude and distribution of the daylight factor in a space are:

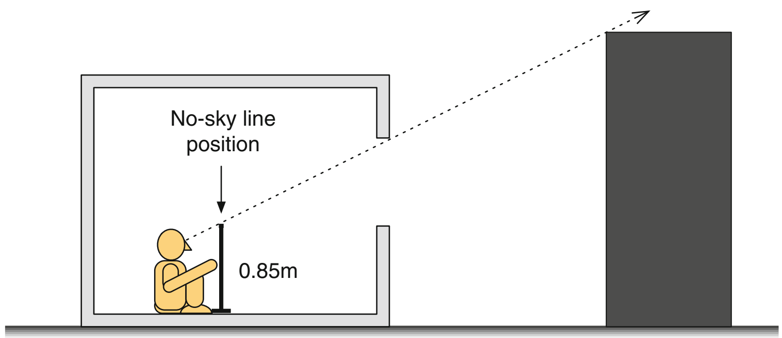
- The size, distribution, location, and transmission properties of the windows
- The size and configuration of the space
- The reflective properties of the internal and external surfaces
- The degree to which the external structures obscure the view of the sky

The importance of reflection in a space is illustrated in Fig. 15 which shows the distribution in daylight factor across a plane at desk height (0.8 m) in a rectangular space 3.0 m wide, 9 m deep, and 2.7 m high (i.e., the same space used for the earlier example). The upper plot shows the distribution in the daylight factor with no inter-reflection of light taking place. This would be the case if all the opaque surfaces had zero reflectance (i.e., perfectly black). This quantity is also known as the direct sky component of the daylight factor since it is entirely due to the sky which is directly "visible" from the point of calculation. The lower plot shows the same distribution but now including the effect of reflection from building surfaces having typical reflectivity values, i.e., 0.7 for the ceiling, 0.5 for the walls, and 0.2 for the floor and external ground. In both cases the daylight factor is greatest closest to the window; however, the proportion of the total that is due to reflected light increases with distance away from the window. At the back of the space, reflected light accounts for more than three quarters of the total daylight factor.

The mean daylight factor across the workplane including inter-reflection is 2.2%. The mean value however is greatly skewed by the high daylight factor values near to the window. The median daylight factor value is only 0.77%, i.e., half the floor area has a daylight factor less than this. One of the measures formulated to determine the evenness of the daylight distribution is called uniformity and it is defined as the minimum daylight factor divided by the mean value for daylight factor. Since the minimum DF value was 0.2%, the uniformity for this space was predicted to be 0.1.



Daylight, Indoor Illumination, and Human Behavior. Figure 15
Example daylight factor



Daylight, Indoor Illumination, and Human Behavior. Figure 16
Estimating the no-sky line

Because the amount of sky visible at the workplane is a governing factor for general illumination, where obstructions are present it is common to estimate the "no-sky line," i.e., that point on the workplane where the sky just ceases to be visible, Fig. 16. If there is no obvious external horizon (i.e., no obstructions outside the window) then, as a rule of thumb, it is common to assume that natural light can penetrate into a space a distance twice that of the floor to ceiling height (for a window that extends from the workplane to the ceiling).

The Contribution of Sun to Daylight The potential for direct sun to enter and illuminate a space is a key consideration in architecture, albeit one that has been traditionally evaluated qualitatively. With scale models this is usually investigated independent of skylight illumination using a simple directional light source called a heliodon to represent the sun, and visually inspecting the resulting shadow patterns across and inside the model. At its most basic, a heliodon could be a small halogen lamp on a movable track. Rather than allowing for a full hemisphere of possible sun positions – and the space it would require – the light source in larger heliodons is usually kept fixed and the scale model is secured to a turntable that is free to rotate in all directions. Thus by positioning the turntable (and attached model) accordingly, it is possible to obtain the correct relative position between the sun (i.e., the light) and the model for a particular time of the day/year [8]. Heliodons have mostly been used by architects and students of architecture.

The shadow pattern approach is essentially qualitative. The brightness of the sun plays no part and light from the sky is not considered. The daylight factor approach (using a sunless sky) and the shadow-pattern approach (using a skyless sun) are essentially incompatible methodologies. Thus it is often difficult to reconcile the (qualitative) outcome of a shadow-pattern study with a quantitative measure of relative illumination under an overcast sky (i.e., a daylight factor). The inability to meaningfully evaluate daylight in its totality – light from the sun and the sky – in a single, unified schema is believed to be one of the major contributing factors leading to poor design decisions, e.g., overglazing of buildings and the ineffective application of brise-soleil. Computer modeling is used nowadays in preference to scale models to generate shadow patterns, and while this may be more convenient, especially for complicated geometries, the fundamental limitations of the approach are the same.

Determination of the Daylight Factor at the Design Stage

The various methods that can be used to predict daylight factors generally fall into one of the following categories:

- Physical, i.e., measurements in a scale model
- Graphical, tabular, and analytical methods
- Computer simulation, e.g., using a program such as *Radiance* [9]

Physical Modeling Architects have for centuries used physical scale models to study various aspects of building design including natural lighting, and the practice is still commonplace today. Daylight factors were first measured in scale models under actual overcast sky conditions. The measurements of internal and (unobstructed) external illuminance need to be taken simultaneously since the illuminance produced by an actual overcast sky can vary significantly over a period of a minute or even shorter. The daylight factor values obtained under actual conditions are to a fair degree approximations since many seemingly overcast skies have luminance patterns that diverge markedly from the CIE standard description [10]. An artificial sky provides a controlled means of illuminating a scale model for the purpose of taking measurements and also for qualitative appraisal [5]. The most common artificial sky is the "mirror box" design. This has a horizontal sheet of white diffusing material forming the top of the box. The sheet is evenly lit from behind (i.e., from above) by lamps. The four vertical sides of the box are mirrors. These create a sky vault that extends seemingly to infinity on all sides due to multiple reflections between the mirrors. Measurements have shown that the luminance pattern in mirror box skies can approximate that of the CIE overcast sky, and so these can provide a controlled luminous environment for the determination of daylight factors. Many of the larger schools of architecture had artificial skies at one time or another, but they tend to be less used since computer-based methods became more common.

Graphical, Tabular, and Analytical Methods The Waldram diagram is one of several graphical methods that were devised in the early 1900s to predict the direct sky component of illumination under simple sky conditions [5]. The principle of the Waldram diagram is that the half hemisphere of sky visible from a vertical window without obstruction is mapped onto a regular grid such that equal areas of the grid correspond to equal values of direct illumination from the sky. This involves applying a distortion to the representation of actual building features, e.g., the outline of a window, so that they can be shown on the diagram. The Waldram diagram is rarely used nowadays for daylighting evaluation, though some practitioners still resort to it for the arcane practice of determining a "right of light" [11].

Tabular methods such as the BRS tables were introduced in the 1950s and widely used at the time, though now they are only of historical interest. One of the many analytical methods commonly used is the equation to predict the average daylight factor. First proposed by Lynes in 1979 [12], the equation was revised by Crisp and Littlefair in 1984 following validation tests using scale models [13]. The revised equation is:

$$\overline{DF} = \frac{TW\theta M}{A(1 - R^2)} \tag{3}$$

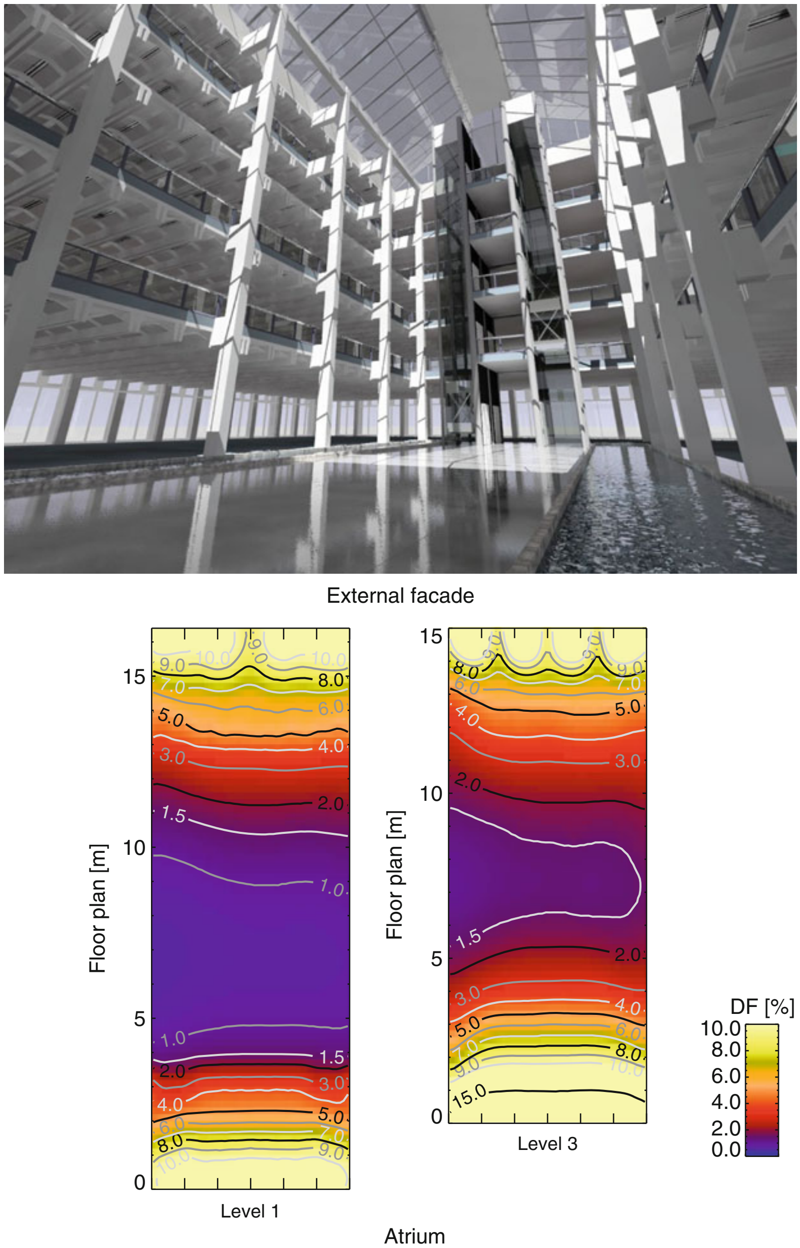
Here T is the effective transmittance of the window(s); W is the net area of side window(s); θ is the angle in degrees subtended in vertical plane by sky visible from the center of a window; M is the maintenance factor; A is the total area of bounding surfaces of an interior, floor + ceiling + walls, including window(s); R is the area-weighted mean reflectance of interior bounding surfaces. The equation is still used as a rule-of-thumb method at the design stage [14].

Daylight Prediction by Computer Simulation Computer programs that could predict internal daylight levels in buildings first became widely available in the late 1980s. One of the most commonly used is the freely available *Radiance* lighting simulation system [9]. Lighting simulation programs need to be distinguished from so-called photo-realistic rendering programs such as 3DS Max. The former, which includes *Radiance*, predict the transport of light in a virtual 3D scene using physically based models for the emission, transmission, reflection, and scattering of light. Thus the output can inform on how the actual building might perform, e.g., in terms of visual impression and predicted illuminance levels for a particular sky condition. Photo-realistic rendering in contrast uses various nonphysical means to quickly generate images that give an impression of what the real scene might look like in terms of its underlying 3D geometry, but the shading (i.e., lighting) applied to the surfaces is largely arbitrary. The image in Fig. 17 is a simulation of an atrium space under sunny sky conditions that was computed using *Radiance*. Below the visualization are two plots showing the distribution in predicted daylight factor (i.e., under CIE standard overcast sky) calculated at the workplane height across the floor plans for levels 1 and 3 (Fig. 17).

Accuracy of Daylight Factor Predictions Unlike scale models used to study thermal, acoustic, and structural properties, physical models for daylighting do not require any scaling factors. Thus the daylight conditions in a faithful scale model replica should be the same as for the full-sized building given identical external conditions. This fundamental property of illumination physics proved so compelling to practitioners, and indeed many researchers, that measurements of illuminance in scale models for daylight factor calculation assumed “benchmark” status even though the accuracy had not been rigorously proven.

One of the definitive studies on the accuracy of illumination studies using scale models was that carried out by Cannon-Brookes in 1997 [15]. The study found that the scale model measurements typically exceeded the illuminances in the actual space by 50–100% for overcast conditions and up to 250% for clear skies with sun. These findings, in addition to the inherent problems associated with sky simulator domes [16], have led most practitioners and researchers to choose computer simulation rather than physical models for the bulk of rigorous, quantitative work.

Computer simulation of lighting quantities including daylight has undergone numerous validation tests since the mid-1990s. The degree and exacting nature of these exceed those which physical modeling has been subjected to by a large margin. In particular, the *Radiance* system has undergone more validation studies than any other program, and many of the tests were under daylight conditions in actual spaces. In what is widely considered to be the definitive validation study of a simulation program under real sky daylight conditions, illuminance predictions from *Radiance* were compared with measurements taken in a full-size office space. Measured sky luminance patterns were “mapped” into the simulation program so that the absolute accuracy of the program could be evaluated without the uncertainties that are introduced when the sky luminance pattern has to be estimated using a sky model. The majority of *Radiance* illuminance predictions were shown to be within ±10% of the measured values [17–19]. This and other studies have led to the widespread adoption of *Radiance* by leading consulting engineers. For both researchers and practitioners worldwide, *Radiance* has become the de facto standard for a wide range of



Daylight, Indoor Illumination, and Human Behavior. Figure 17
Visualization of atrium under sunny sky conditions and daylight factor plots under the CIE standard overcast sky

applications, not least the evaluation of daylight in buildings [20].

It needs to be borne in mind that validation studies reveal the *potential* accuracy of a daylight simulation program, and that the high accuracy shown in tests can only be approached in "live" projects if strict quality-control procedures are employed. Users of daylight simulation programs such as *Radiance* need to be fairly skilled and, ideally, have a good appreciation of the issues involved, e.g., how to construct a 3D model that is suitable for lighting simulation and how to set to key parameters for the simulation. Studies have revealed that users presented with the same design can produce widely differing predictions for, say, daylight factors, and that suitable training in the use of the simulation tool is vital [21].

Despite the proliferation of computer-based tools for building evaluation and their proven accuracy, scale models still have a great appeal, especially to architects, because they offer an immediate and almost tactile feel for the relation between building geometry, surface properties, and the character of illumination. This is especially apparent when the spatiotemporal dynamic play of light in a model is observed using a heliodon to mimic the progression of sunlight through the day.

The Daylight Factor and Standards

Codes, standards, and guidelines for daylighting are invariably advisory rather than mandatory. As noted earlier, codes, etc., worldwide are almost all founded on the daylight factor. One of the key standards documents for daylight in buildings is the British Standard 8206–2 *Lighting for buildings – Part 2: Code of practice for daylighting* [22]. That document gives the following recommendation:

- It is considered good practice to ensure that rooms in dwellings and in most other buildings have a predominantly daylit appearance. In order to achieve this, the average daylight factor should be at least 2%. If the average daylight factor in a space is at least 5% then electric lighting is not normally needed during the daytime, provided the uniformity is satisfactory. If the average daylight factor in a space is between 2% and 5%, supplementary electric lighting is usually required.

For uniformity, the same standard advises that

- . . . the minimum illuminance on a particular task area should not fall below 0.7 times the average illuminance on that task area.

This indicates that, for the 2% average criterion, the minimum daylight factor should be no less than 1.4%. It is instructive to compare this advice with the daylight factor distribution for a deep-plan office space shown in Fig. 15b. Although the mean daylight factor meets the requirement of 2%, the uniformity value for the space was only 0.1, much lower than the recommended minimum of 0.7. The median value of just below 0.8% better indicates just how much of the space falls below the minimum value of 1.4%. This simple example shows that there are quite fundamental limitations to the depth of daylight (strictly, *daylight factor*) penetration that can be achieved using only vertical glazing from one direction. Strategies to extend the penetration of daylight from perimeter windows include having large floor to ceiling heights with tall or clerestory windows (see section on "Daylighting Strategies"). If the window receives significant sun, then a light-shelf (Fig. 6) might serve the dual purpose of shading near to the window and redirecting sunlight deeper into the space. Note, however, that the effectiveness of a light-shelf design cannot be directly assessed using the daylight factor since neither sunlight nor sunny sky conditions figure in the evaluation.

Recommended Daylight Factor Values A set of daylight factor values as might be typically recommended in various guideline documents are presented in Table 1. Historically, the recommended values for factories have been high since these were often large-area, single-story buildings which could be very effectively daylit by rooflights (invariably configured to avoid the ingress of direct sun).

Daylight, Indoor Illumination, and Human Behavior. Table 1 Typical daylight factor values recommended in guidelines during the latter half of the twentieth century

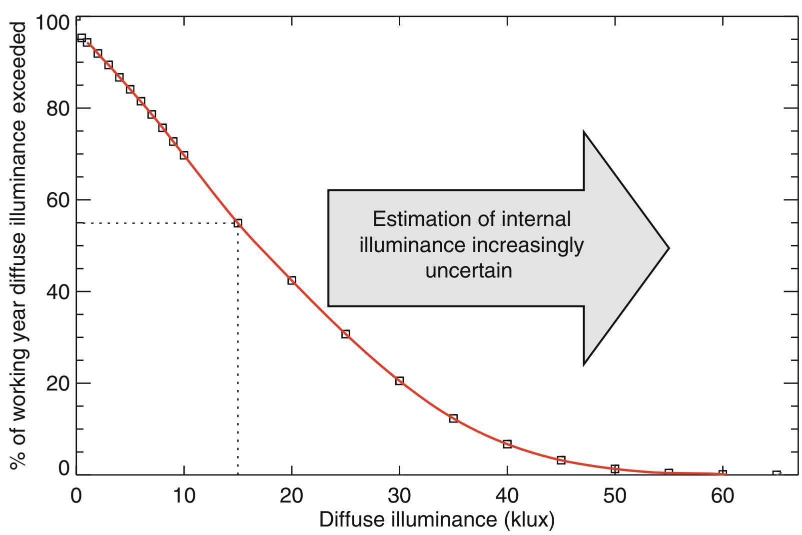
Nondomestic buildings	
Church	1% minimum
Factory	5% minimum
Office	2% minimum
Classroom	2% minimum
Hospital ward	1% minimum
Dwellings	
Bedroom	0.5% at 3/4 of room depth
Kitchen	2% at half of room depth
Living room	1% at half of room depth

Deriving Absolute Values from Daylight Factors It is possible to convert a daylight factor value (i.e., a relative measure of illumination under a static sky condition) into an estimation of the annual provision of daylight using cumulative diffuse illuminance availability curves. An example curve based on measurements taken at Kew (near London, UK) is shown in Fig. 18. This curve gives the percentage of the year for which a diffuse horizontal illuminance is achieved during, say, normal working hours – in this case 09:00 to 17:30. Applying a simple technique, cumulative internal illuminance availability can be estimated from daylight factor values and the curves (or similar charts) of cumulative diffuse sky illuminance [23]. This gives a first-order approximation to annual daylighting provision from which supplementary lighting requirements can be estimated.

For example, suppose that the minimum required internal illuminance at a point in an office is 500 lux, and that a daylight factor evaluation using the CIE standard overcast sky (equation, scale-model or simulation) predicts a daylight factor value of 3.3%. The minimum diffuse sky illuminance which provides an average internal illuminance of 500 lux is therefore:

$$\frac{500 \times 100}{3.3} \approx 15,000 \quad (4)$$

It can be determined from Fig. 18 that a diffuse sky illuminance of 15,000 lux is exceeded for about 55% of the normal working time. The CIE standard overcast sky is likely to be a reasonable approximation to some of the duller skies in the cumulative distribution. However, only about 40% of the skies in the Kew climate file for the UK can be classed as heavily overcast [18]. For locales sunnier than the UK, the percentage of overcast skies throughout the year will of course be lower. The fundamental weakness of this approach is that it tries to extend the daylight factor modeling paradigm (i.e., relative illumination under standard overcast sky conditions) to somehow account for the illumination effect of non-overcast skies. Since real non-overcast skies diverge enormously from overcast sky luminance patterns, the estimations of illuminance from the non-overcast skies in the distribution will be greatly in error. Additionally, the method cannot of course account for the illuminance contribution of the sun – either directly or from reflection. Thus the divergence between estimation and reality increases as higher illuminances in the cumulative distribution are considered (Fig. 18). Needless to say, this approach is highly inappropriate for building designs where the redistribution of direct beam radiation to provide diffuse illuminance is a significant feature of the daylighting system, as is the case with designs that make use of deep window



Daylight, Indoor Illumination, and Human Behavior. Figure 18
Cumulative diffuse illuminance availability, Kew, UK

reveals, light shelves, light wells, etc. Indeed, redirection of direct beam illumination will occur in all buildings to a greater or lesser degree even when it is not an explicit design feature. Despite the limitations, the cumulative illumination approach must be considered to be an advance on the daylight factor alone because the results, however flawed, do at least depend on absolute measures of the climate for the locale. In other words, the results for St. Petersburg will be different to those for Cairo. The effect of building orientation on internal illuminance, i.e., the difference between north- and south-facing glazing, can be roughly estimated by applying so-called orientation factors [24]. However it is believed that this is hardly ever used by practitioners.

Daylight Guidelines Post 2000 Since the year 2000, the role that daylight evaluation plays in the design process has acquired a new impetus as the need to demonstrate compliance with various "performance indicators" becomes ever more pressing. Two of the most used rating systems are BREEAM (The BRE Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) which originated in the UK and USA, respectively, though they are both used worldwide [25, 26]. Both the LEED and the BREEAM websites chart the growth in the building projects that have been certified using the respective schemes. These and similar rating systems are actively promoted by government departments and lobby groups. As a consequence, building designers are resorting more and more to prediction methods (invariably simulation) as a means of demonstrating compliance with the various schemes [20]. This, one might reasonably hope, would lead to noticeable improvements in the practice of design evaluation, which in turn should improve the likelihood of realizing a well-daylit building. However, basing design evaluation on the daylight factor has not been proven to result in better daylit buildings.

The Daylight Factor and Actual Daylighting Conditions

The daylight factor was formulated long before the computation of actual illumination levels became a practical possibility. Thus the simplifications inherent in the formulation were, back then, a necessary expediency. As noted, a major issue with the daylight factor is that actual daylight illumination conditions deviate markedly from that described by the overcast sky paradigm. This is so even for Northern Europe where there is a commonly held belief that skies are "mostly" overcast and so use of the daylight factor as a basis for evaluation is justified. A paper by Littlefair in 1998 gives annual cumulative internal illuminance measurements for a point in similar rooms with north- and south-facing glazing [27]. The rooms were unshaded and unoccupied. An illuminance of 200 lux was achieved for approximately 58% and 68% of the year for the north- and south-facing spaces respectively. However, an illuminance of 400 lux was achieved for only 12% of the year for the north-facing space with more than four times that occurrence (51%) for the south-facing space. Of course, for sunnier climates the effect of orientation on daylight illumination will be greater still.

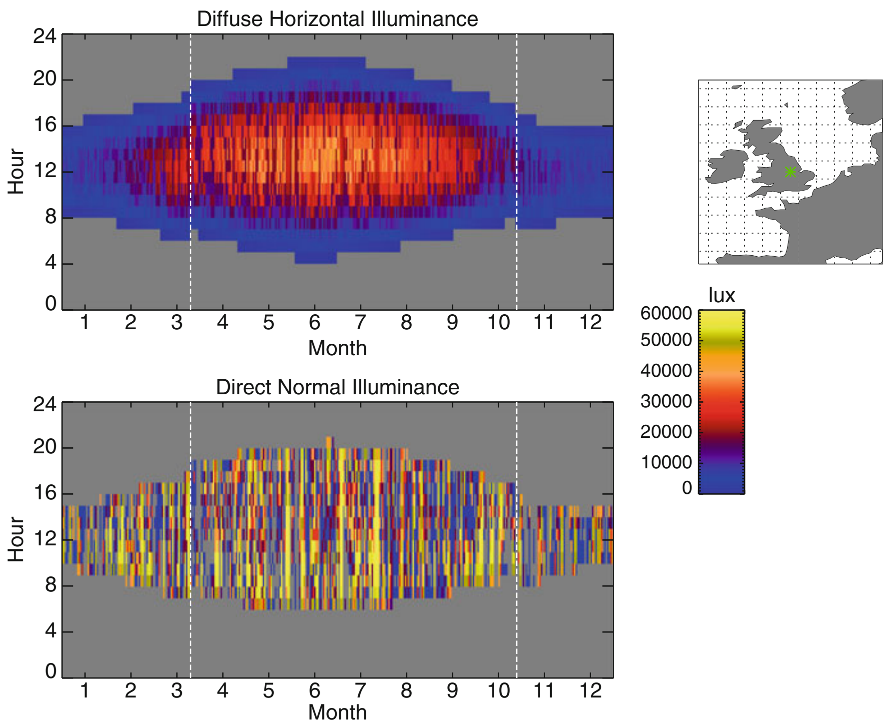
An unfortunate consequence of the long-standing and often uncritical use of the daylight factor is that the terms "daylight" (as defined in the Introduction) and "skylight" are often used interchangeably. This leads to confusion where precise definitions are required. Some of this muddle has resulted from the conflation of "daylight" per se with what is predicted by the daylight factor. For example, expressions such as "the daylight factor was used to evaluate daylight levels" are common in both research and practice literature. The daylight factor is precisely what it was defined to be: a ratio of illuminances under a specific sky condition. The daylight factor therefore is, in reality, a proxy for actual daylight illumination. Thus, what the daylight factor communicates is in fact very different from the actual illumination levels that result from the full range of naturally occurring sun and sky conditions.

Extending the basis of the daylight factor approach by incremental means has proved problematic. It is a straightforward matter to use in a daylight simulation non-overcast sky conditions, e.g., the CIE clear sky luminance pattern with sun (see Fig. 17). To be useful for evaluation purposes however, the luminous output of the sun and sky must be known since absolute values and not ratios must be considered. Extending the daylight factor notion of ratios to non-overcast skies with sun results in essentially meaningless values and should be avoided. When absolute values for luminous quantities are predicted (e.g., lux at the workplane) then the values used to normalize the output from the sun and sky must be justified, e.g., diffuse horizontal illuminance for the sky and direct normal illuminance for the sun. Ideally, these should be based on typical values for, say, a clear, sunny day in summer. The predicted quantities however will be of very limited value for any estimation of prevailing daylight levels in the building since they are indicative only of conditions for particular sun and sky conditions occurring at a particular time of the day/year. In other words, such an evaluation would offer merely a single "snapshot" of the multitude of naturally occurring daylight conditions due to all the possible combinations of sun and sky conditions occurring at various times throughout the year. Estimating overall daylighting performance from snapshot evaluations could be highly misleading. The parameters governing the availability of daylight do not lend themselves to any form of averaging. While it can be informative to determine, say, a monthly average for a scalar quantity such as temperature, illumination is strongly dependent on the directional character of the incident light. Associated with every non-overcast sky and sun condition are the solar altitude and azimuth which, of course, vary continuously throughout the day. In terms of providing a basis for predicting measures of illumination, the notion of "average" days is less than useful because an "average" sun position would give entirely misleading patterns of illumination. Some guidelines (e.g., LEED and ASHRAE) have allowed so-called clear sky options where a specified daylight illuminance must be achieved (usually at the workplane) for clear sky conditions at a particular time, e.g., at noon on the equinox. These approaches are problematic for a number of reasons. In particular, some of them provide no guidance on normalizing the sky output, a significant omission since absolute values are now the target. Furthermore, the method seems to recommend evaluation under clear sky conditions *without* a sun – a physically impossible illumination condition in nature.

The true nature of illumination from the sun and sky for any particular locale can only be appreciated by examining the luminous output from both the sun and the sky over a period of a full year. The principal sources of annual climate data are the standard weather files which were originally created for use by dynamic thermal modeling programs [28]. These datasets contain hourly averaged values for a full year, i.e., 8,760 values for each parameter. The key daylight parameters stored in the weather files are the diffuse horizontal illuminance and the direct normal illuminance. The diffuse horizontal illuminance is the visible light energy from the unobstructed sky that is incident on a horizontal surface. The direct normal illuminance is the visible light energy from the sun that is incident on a surface which is kept normal to the beam of radiation, i.e., the photocell always "points" directly to the sun. If the climate file contains only irradiance (i.e., total energy values), then it is converted to illuminance using a luminous efficacy model [29].

A visualization of the illuminance data from a standard weather file is given in Fig. 19. The time-series data of 8,760 values has been rearranged into an array of 365 days (x-axis) by 24 h (y-axis). The shading at each hour indicates the magnitude of the illuminance – see legend – with zero values shaded gray. Presented in this way it is easy to appreciate both the prevailing patterns in either quantity and their short-term variability. Most obvious is the daily/seasonal pattern for both illuminances: short periods of daylight in the winter months, longer in summer. The hour-by-hour variation in the direct normal illuminance is clearly visible, though it is also present to a lesser degree in the diffuse horizontal illuminance (i.e., light from the sky). The data is for Nottingham, UK, the location of which is identified in the map above the legend. Local time is shown, i.e., summertime is local time plus one hour. The start and end period of summertime are indicated by vertical dashed lines in each of the figures. Recall the patterns of indoor illumination for the four components of daylight given in Fig. 3. Each of the 4,380 (i.e., the daylight hours) unique combinations of sky and sun conditions in the weather file (Fig. 19) will result in a unique pattern of internal daylight illumination.

Both diffuse and direct illuminances will, in reality, vary over periods much shorter than an hour. Interpolation of the dataset to a time-step shorter than one hour will provide a smoother traversal of the sun, which may be necessary when using the data for simulation of daylight. Interpolation alone, however, will not introduce short-term variability into the values for diffuse horizontal and direct normal illuminance.



Daylight, Indoor Illumination, and Human Behavior. Figure 19
Illuminance data from the CIBSE standard climate file for Nottingham

If required, this variability would have to be synthesized using stochastic models [30].

The illuminance data in the standardized weather files reveal the true nature of the patterns in daylight illumination from the sun and the sky. It is also evident from the visualization of the data (Fig. 19) that any "snapshot" evaluation using just part of the data would not be representative and could lead to highly flawed conclusions regarding the daylighting performance of the building. How these data might be used in their entirety to better predict actual building performance is described in the section on "Climate-Based Daylight Modeling."

Human Factors and Daylight

Daylight and Visual Comfort

A good provision of daylight is now considered to be highly desirable in terms of improving occupants' well-being and productivity [31, 32]. Daylight, however, can cause visual discomfort by inducing glare and veiling reflections. Efforts to control glare often result in the loss of predicted daylight benefit as occupants deploy blinds, etc., which may remain closed long after the glare condition has diminished.

In the CIBSE Lighting Guide LG7, glare is defined as a "Condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts" [33]. There are two types of glare: disability glare, where stray light reaching the eye results in a reduction of visibility and visual performance, and discomfort glare, which leads to users' discomfort, often with less immediately noticeable effects such as headaches or posture-related aches after work. Glare can be caused by direct sunlight through a window or by the luminance differences between bright areas such as windows with bright sky views and the darker task area. Furthermore, veiling reflections on reflective surfaces such as computer screens can affect visual comfort at workstations facing away from the window.

The majority of office workers now use (vertical) computer screens during all or part of their workday [34]. They are far more likely to be affected by glare from windows than their counterparts of 10 or 20 years ago who were largely occupied with paper-based tasks on horizontal surfaces [35]. It is considered an imperative, therefore, to attempt to minimize glare when designing for daylight provision in offices. Current international and European standards regarding visual comfort in the office environment aim to address this issue (EN ISO 9241–7:1998, EN 12464–1:2002, EN 29241–3:1993). A number of guidelines have been published which aid designers and architects in their efforts to reduce glare in order to achieve comfortable visual environments, such as the CIBSE Lighting Guides LG3 and LG7, the Code for Lighting [36], and CIBSE Guide A [4].

While there are accepted, albeit imperfect, models for the potential glare effect of (fixed output) luminaires, it is recognized that glare from daylight sources is poorly understood [37]. The first daylight glare formulations were extrapolations from studies of discomfort glare due to artificial lighting [38]. The light sources used in those studies subtended relatively small solid angles from the viewpoint of the subject, and the luminance conditions (source and environment) were very different from typical daylit offices. In short, those extrapolations proved to be inadequate for the purpose of determining discomfort glare from daylight. There have been a number of attempts to improve glare formulations for use in daylight situations, such as Daylight Glare Index (DGI), Unified Glare Rating (UGR), and the New Daylight Glare Index (DGIN), but the problem persists. A review in 2005 by the chair of the International Commission on Illumination (CIE) Technical Committee on glare concluded that the "available assessment and prediction methods are of limited practical use in daylit situations" [37].

Numerous field studies have been carried out in order to investigate glare from daylight through windows. The earliest discomfort glare studies used large-area artificial light sources to mimic the effect of daylight through windows [5]. However, the sensation of discomfort that may arise from staring at a featureless (artificial) light source seems to be very different from that produced by viewing a comparably high-luminance natural scene [39, 40]. Moreover, as outlined in a recently published review of research regarding occupant satisfaction with the luminous environment, there are multiple additional factors that affect occupants' visual comfort, such as preferred light levels and access to lighting and shading controls [32]. Studies which have included occupant surveys in combination with controlled measurements of the luminance were often set in laboratory environments quite different from the usual workplace.

Considering that the natural variability in daylight contains seasonal, daily and short-term components and that discomfort glare is known to depend strongly on directional factors as well as the scalar magnitude and distribution of the luminous field, findings from existing studies have limited use when describing glare conditions experienced in real office spaces. Value judgments appear to be the only ground on which discomfort from glare may be assessed, but it is nevertheless essential that these subjective assessments are linked to objective and quantifiable data or phenomena [37]. New approaches to assessing glare that may overcome the current limitations in understanding are described in the section "New Approaches to Measuring the Daylit Environment."

Daylight and Health/Productivity

The primary concern in the daylighting of buildings has generally been to provide illumination for task, e.g., 500 lux on the horizontal workplane. However, in the last few decades there has been a gradual increase in awareness of the nonvisual effects of daylight/light received by the eye [41]. (We exclude from consideration here skin exposure effects such as tanning and the production of vitamin D.) It is well known that building occupants almost without exception will prefer a workstation with a view of the outdoor environment to a windowless office [42]. A view to the outside indicates of course the presence of daylight, although the relation between view and daylight provision is not straightforward, being dependent on many factors. Might there be productivity and well-being benefits in providing building occupants with well-daylit spaces? In addition to subjective preferences for daylit spaces, it is now firmly established that the light has measurable biochemical effects on the human body, in particular with respect to maintaining a healthy sleep-wake cycle. Could the quality and nature of the internal daylit environment have a significant effect on the health of the human body which can be proven through the measurement of, say, hormone levels? Evidence is suggestive of links between daylight exposure and both health and productivity; however, there is insufficient knowledge at present to conflate these two effects and so they are discussed separately in the following sections, beginning with health.

Health The daily cycle of day and night plays a major role in regulating and maintaining biochemical, physiological, and behavioral processes in human beings. This cycle is known as the circadian rhythm – the term "circadian" comes from the Latin circa, "around," and diem or dies, "day," meaning literally "approximately one day." Circadian rhythms occur in almost all organisms from bacteria to mammals. The circadian rhythm is endogenous meaning that it is produced from within the organism, i.e., what is commonly referred to as the "body clock." However, for many organisms the cycle needs to be adjusted or entrained to the environment by external cues, the primary one of which is daylight.

The primary circadian "clock" in mammals is located in the suprachiasmatic nucleus (or nuclei) (SCN), a pair of distinct groups of cells located in the hypothalamus. The SCN receives information about illumination through the eyes. The retina of the eye contains not only the well-known photoreceptors which are used for vision (i.e., rods and cones) but ganglion cells which respond to light and are called photosensitive ganglion cells. The SCN in turn coveys signals to the pineal gland, which, in response, controls the secretion of the hormone melatonin. Secretion of melatonin peaks at night and ebbs during the day, i.e., its presence modulates the wake/sleep patterns.

The failure to maintain a circadian rhythm that is firmly entrained to the natural 24-h cycle of daylight results in many negative health outcomes for humans, though not all are fully understood. The degree and severity of the outcomes usually depends on the period over which the cycle is disturbed. A transitory disturbance to the circadian cycle familiar to many who have experienced a long-haul flight is jet lag. When traveling across a number of time zones, the body clock will be out of synchronization with the destination time, as it experiences daylight and darkness contrary to the rhythms to which it has grown accustomed. Depending on the individual, it can take a few days to reset the body clock to the local day-night cycle.

Less immediately obvious in its effects than jet lag is the chronic persistence of a poorly entrained circadian rhythm. This was first noticed in shift-workers; however, it is believed to be one of the factors in the increasing occurrence of sleep-disturbance and related conditions in the wider population of the developed world [43]. While the symptoms of sleep-disturbance can be at first mild, e.g., sleepiness, fatigue, and decreased mental acuity, the long-term persistence of the condition may result in significant impacts on both health and worker productivity.

The duration, intensity, and spectrum of the light received at the eye are the principal factors determining the degree of nonvisual effect, and thus a key factor in the entrainment of the circadian cycle. Another important factor is the time of day when the light is applied. Compared to the luminous efficiency function of the eye which has a peak value at 555 nm, the action spectrum for the suppression of melatonin is known to be shifted to the blue end of the spectrum and has a peak around 450–480 nm [44]. The relative suppression of melatonin as a function of light intensity and color temperature for artificial lighting was determined by Mclntyre et al. in 1989 [45]. The illuminances at the eye required for the effective suppression of melatonin are of the order of 1,000 lux depending on the spectrum. Note that the vertical illuminance at the eye is typically one fifth that delivered to the horizontal workplane by (overhead) artificial lights. Thus, a workplane illuminance of around 5,000 lux (much higher than the typical design levels of 300–500 lux) would be needed to provide 1,000 lux at the eye. Thus it is argued that interior lighting levels, as currently recommended and practiced, may be insufficient for circadian regulation [46]. Daylight often provides illuminances significantly higher than the design level, though this is only in close proximity to windows and perhaps also highly daylit spaces such as atria. If the typical illuminances in these zones are high – but not so great that blinds are needed – then those building users that regularly occupy the well-daylit spaces may perhaps experience stronger and more regular circadian entrainment stimuli than those users away from windows who are habitually exposed to lower illuminance at the eye level. These considerations have resulted in the notion that a building through its daylighting may possess a *circadian efficiency* [47]. However, such assertions are presently highly speculative and should be treated as such until the evidence becomes more compelling [48].

There is some evidence that daylight exposure can affect postoperative outcomes in patients and, consequently, that daylight should be a consideration in hospital design. One of the key studies in the literature is that by Walch et al. on patients recovering from elective cervical and lumbar spinal surgery. The patients were housed on either the "bright" or "dim" side of the same hospital unit. The study determined that sunlight exposure was associated with both improved subjective assessment of the patients and also reduced levels of analgesic medication routinely administered to control postoperative pain [49].

Productivity and Performance Bright lighting is generally believed to make people more alert, and well-daylit spaces are generally perceived by occupants to be "better" than dim gloomy ones. The link between objective measures of productivity and the quality of the daylit environment is however elusive because worker productivity is influenced by numerous factors, and it is proving challenging to isolate the effect of just daylight. Furthermore, it is generally not a practical option to monitor the long-term daylight exposure for hundreds of subjects using light meters. Thus the daylighting potential is often estimated from space parameters that can be easily assessed by a site visit. This adds another measure of uncertainty to these studies since daylight exposure itself is a highly variable quantity. Some reports are mostly anecdotal, e.g., good daylighting has been identified as a factor in staff retention [50].

Perhaps the best known studies that have attempted to link productivity to daylight are those carried out by the Heschong-Mahone Group (HMG) in California, USA. The HMG schools' study claimed that

> ... students with the most daylighting in their classrooms progressed 20% faster on math tests and 26% on reading tests in one year than those with the least daylight. Similarly, students in classrooms with the largest window areas were found to progress 15% faster in math and 23% faster in reading than those with the least window areas. Students that had a well-designed skylight in their room, one that diffused the daylight throughout the room and allowed teachers to control the amount of daylight entering the room, also improved 19% to 20% faster than those students without a skylight [51].

Other studies by HMG have made similarly compelling claims in improved productivity for office workers and larger retail sales in well-daylit compared to poorly daylit spaces [52, 53]. However, until independent studies corroborate these reports, the findings must be considered suggestive of an effect rather than conclusive proof of a strong relationship between daylight and productivity/performance [54].

It should be noted that improved productivity has also been claimed for exposure to higher than usual levels of artificial lighting. In many regards, it is easier to isolate the effects of short periods of enhanced artificial lighting than it is for long periods of (highly variable) daylight. A Japanese study found that bright lighting in the office (2,500 lux compared to 750 lux, provided for 2 h in the morning and 1 h after lunch for several weeks) boosted alertness and mood, especially in the afternoon. It also seemed to promote melatonin secretion and fall in body temperature at night, changes that should improve the quality of sleep. Although this work was based on a small number of people and further work is needed, it shows promise for alterations in office lighting in terms of productivity and health of the workers [55]. These findings have led to developments in the use of artificial lighting where controlled exposure across the entire floor-plate of a building is a straightforward matter [56].

Daylight and the User Operation of Lights and Shades

Almost all the commonly used spaces in side-lit buildings will have some form of shading device, e.g., venetian blinds, that is either user-deployed or automatically controlled. Even if the fixed architectural form offers effective shading from direct sun much of the time, there are, nevertheless, likely to be occasions when blinds will need to be used to block either direct sun and/or the view of bright patches of sky. Blinds are usually formed either from individual sections called slats or are continuous. Slatted blinds can have either horizontal or vertical slats.

Users entering a space where there is little daylight will of course switch on the electric lights. The probability that users switch on electric lights was found to be correlated with the minimum daylight illuminance on the working plane [57]. The correlation presented by Hunt in 1980 was based on just a handful of samples and there was considerable scatter in the switch-on probability when the daylight illuminance was in the range 50–500 lux, which is typical of the range experienced in many buildings. A later study provided support for the Hunt model, but as with the original study there was large scatter in the measured daylight illuminances that triggered the switching on of lights [58]. In addition to the switch-on probability, there will also be switch-off probabilities. Relatively little field study data has been published regarding switch-off behavior, and determining a correlation with daylight is more confounding than for switch-on since other factors come into play. For example, switch-off probabilities could be significantly determined by the overall appearance of the space and the particular design of the lights, since it is sometimes not obvious to the occupant that lights have been left on when daylight provision is high.

In an effort to account for the variability in occupants' light switching behavior, stochastic models were introduced in 1995 by Newsahm et al. [59]. This means that whenever a (simulated) user is confronted with a control decision, i.e., to switch on the lighting or not, a probabilistic (i.e., stochastic) process is initiated that determines the outcome of the decision. This approach was further refined by Reinhart in a model designated "Lightswitch-2002," which provides a unified modeling framework for both the switching on and off of electric lights and the operation of blinds/shades to control direct sun [60]. A key input parameter for the Lightswitch-2002 is the user type, of which there are four in the model. The type determines the degree to which the simulated user attempts to make the most of the daylight contribution by both optimizing the blinds and switching off unnecessary artificial lighting, and the results for, say, predicted energy use for lighting are highly sensitive to the assumed type.

Recent Advances in Daylighting

The consideration of daylight in buildings has recently undergone a radical reevaluation. For much of the latter half of the twentieth century, the "objective" evaluation of a building design relied almost exclusively on the daylight factor (section "The Daylight Factor"). Of arguably greater value than a daylight factor analysis was the advice of an experienced daylight designer. Although they commonly make use of the daylight factor, the real value of the designer's expertise however is in envisioning those many aspects of daylight provision that are *not* accounted for by the daylight factor. These aspects are many and varied. Key amongst them, however, are the contribution of the sun to the overall illumination of the building and the potential for glare resulting from direct sun and/or skylight. The first of these – the illumination contribution of the sun – can only be very approximately estimated. In truth, it is a qualitative judgment founded on experience and intuition rather than numerous computations of light transfer. The second depends in part on a consideration of geometrical relations between the progression of the sun and the configuration of the building, i.e., the windows of the building, their orientation, and any nearby obstructions. This involves envisioning the progression of the sun-illuminated surfaces inside the building, and estimating the potential for views of bright sky that might be a cause for glare. In other words, for either case there is an envisioning of sorts by the daylighting expert of the spatio-temporal dynamics of daylight illumination. These evaluations can be informed to a limited degree by shadow pattern studies of solar penetration. In addition, of course, an experienced designer will offer advice on a great many other, secondary aspects of daylighting design for the building. However valuable the advice offered by the daylight designer, it is not something that could be distilled into a codified scheme and, ultimately, some numerical measure of predicted performance. If daylighting experts were not part of the design team, then a routine daylight factor evaluation accompanied perhaps by a shadow-pattern study would be the sum total of the "daylighting evaluation." Thus a completed building with good daylighting was more likely to be a product of chance and good fortune than design. Inevitably, continued reliance on the half-century-old daylight factor led also to a sense of stagnation in sectors of the daylighting research community.

Two seemingly concurrent, but out-of-step and totally independent, developments have changed both the perceived importance and the nature of daylight evaluations. The first is the increasing demand to demonstrate compliance at the design stage with recommended measures of building performance, e.g., the LEED rating system. The need for this appears to be widely accepted throughout the developed world, and the rate of uptake by practitioners is ever increasing in response to pressure and encouragement from governments, regulatory bodies, etc. For those striving to effect good daylighting design, however, the race for compliance is by no means entirely good news because the recommendations are founded on schema such as the daylight factor that ignore fundamental parameters such as building orientation and prevailing climate. The second development is a major advancement in the way that daylight evaluations are carried out. This advancement, called climate-based daylight modeling, can address the very real concerns that practitioners and researchers are now voicing regarding the high potential for "compliance chasing" resulting in poor design choices for buildings [61]. An important addition to these developments is the emergence of an array of new facade and glazing technologies for improving the daylighting of buildings, both new and existing. And in the last five years, camera-based measurement techniques that can characterize the luminous environment with an unprecedented level of coverage have become available to everyday practitioners. These developments, recently established and emerging, are described in the following sections.

Climate-Based Daylight Modeling

Climate-based daylight modeling is the prediction of various radiant or luminous quantities (e.g., irradiance, illuminance, radiance, and luminance) using sun and sky conditions that are derived from standardized annual meteorological datasets. Climate-based modeling delivers predictions of absolute quantities (e.g., illuminance) that are dependent both on the locale (i.e., geographically specific climate data is used) and the fenestration orientation (i.e., accounting for solar position and nonuniform sky conditions), in addition to the space's geometry and material properties. The operation of the space can also be modeled to varying degrees of precision depending on the type of device (e.g., luminaire and venetian blinds) and its assumed control strategy (e.g., automatic, by occupant, or some combination). The computational overhead and complexities introduced when attempting to model the operation of the space are discussed later.

The term "climate-based daylight modeling" does not yet have a formally accepted definition – it was first coined by Mardaljevic in the title of a paper given at the 2006 CIBSE National Conference [62]. However, it is generally taken to mean any evaluation that is founded on the totality (i.e., sun and sky components) of time-series daylight data appropriate to the locale over the course of a year. In practice, this means sun and sky parameters found in, or derived from, the standard meteorological data files which contain 8,760 hourly values for a full year. Given the self-evident nature of the seasonal pattern in sunlight availability, a function of both the sun position and the seasonal patterns of cloudiness, an evaluation period of 12 months is needed to capture all of the naturally occurring variation in conditions that is represented in the climate dataset. It is also possible to use real-time monitored weather for a given time period, if calibration to actual monitored conditions within a space is desired. Standardized climate datasets are derived from the prevailing conditions measured at the site over a period of years, and they are structured to represent both the averages and the range in variation that typically occurs. Standard climate data for a large number of locales across the world are freely available for download from several websites. One of the most comprehensive repositories is that compiled for use with the EnergyPlus thermal simulation program [63]. This contains freely available climate data for over 1,200 locations worldwide.

There are a number of possible ways to use climate-based daylight modeling [64–68]. The two principal analysis methods are cumulative and time-series. A cumulative analysis is the prediction of some aggregate measure of daylight (e.g., total annual illuminance) founded on the cumulative luminance effect of (hourly) sky and the sun conditions derived from the climate dataset. It is usually determined over a period of a full year, or on a seasonal or monthly basis, i.e., predicting a cumulative measure for each season or month in turn. Evaluating cumulative measures for periods shorter than one month is not recommended since the output will tend to be more revealing of the unique pattern in the climate dataset than of "typical" conditions for that period. The cumulative method can be used for predicting the microclimate and solar access in urban environments, the long-term exposure of art works to daylight, and quick assessments of seasonal daylight availability and/or the requirement for solar shading at the early design stage. Time-series analysis involves predicting instantaneous measures (e.g., illuminance) based on each of the hourly (or sub-hourly) values in the annual climate dataset. These predictions are used to evaluate, e.g., the overall daylighting potential of the building, the occurrence of excessive illuminances or luminances, as inputs to behavioral models for light switching and/or blinds usage, and the potential of daylight responsive lighting controls to reduce building energy usage. Thus a daylight performance metric would need to be based on a time-series of instantaneously occurring daylight illuminances since these cannot be reliably inferred from cumulative values. As noted, evaluations should span an entire year. There is some debate as to whether the daily time period of analysis should be all daylit hours, which vary in length with the seasons, a standardized "working day" of 8, 10, or 12 h, or the actual occupancy pattern of the space. Different purposes are likely to favor different daily analysis periods.

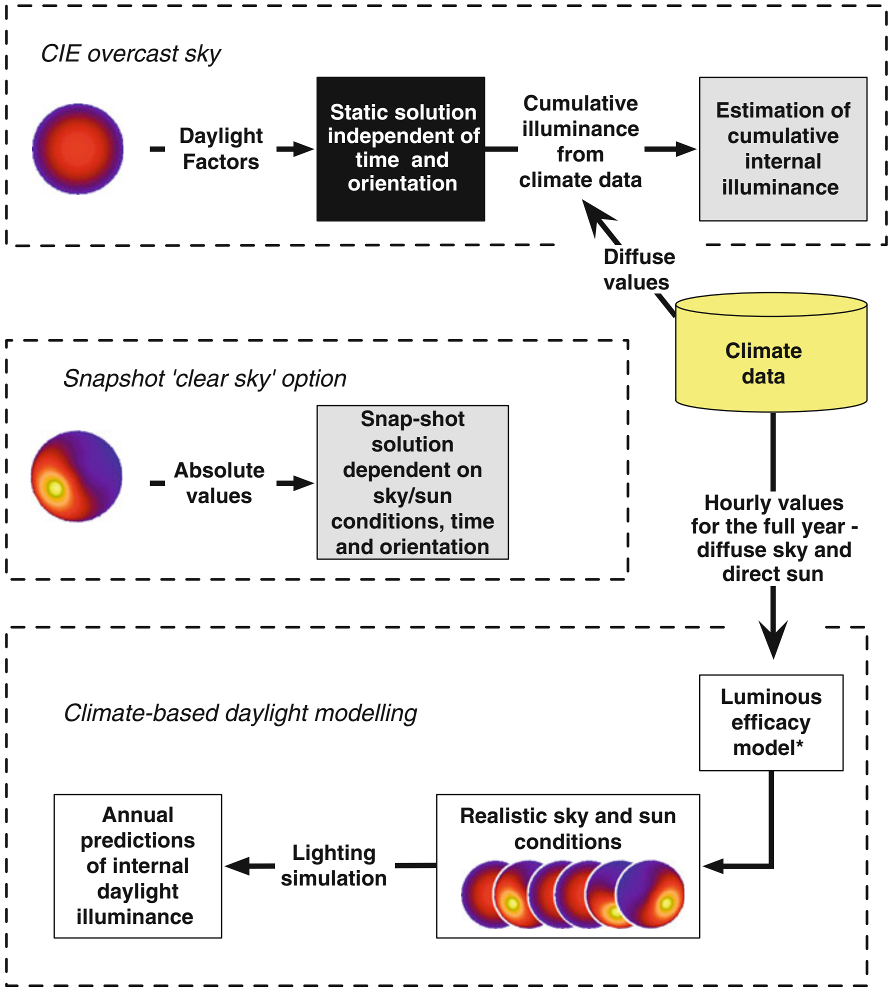
How climate-based modeling compares to the standard method (daylight factors) and the more recent "clear sky options" is shown in Fig. 20. A daylight factor value can be converted into an estimate of the overall occurrence of daylight in a space by using a diffuse illuminance availability curve for that locale (as described in an earlier section). However, since the contribution of sunlight cannot be accounted for, the method must be considered a crude estimator. The various "clear sky" options generally do not require that the skies are normalized. Thus there is no link with prevailing climate. In contrast, climate-based daylight modeling uses the full year of irradiance or illuminance data found in the climate file, and derives the instantaneous sky and sun conditions from these.

Daylight Metrics

The purpose of a metric is to combine various factors that will successfully predict better or worse performance outcomes and so inform decision making. Performance may be described by more than one metric, i.e., it is not necessary to combine all significant factors into one metric. This implies a preference for simplicity so they can be intuitively understood, and a direct relation to measurable outcomes made. When metrics are sufficiently refined and understood and their predictive capabilities validated, then performance criteria can be set for various guidelines and recommendations.

As has been noted, metrics founded on the daylight factor are relatively straightforward since there is no time-varying component and so they simply report on the DF value at a point, some average DF value across a workplane, or perhaps some measure of uniformity of the DF across the workplane. Metrics founded on climate-based modeling are potentially far more complex since the simulations output illuminance data at each time-step for every point in the space. Thus, for all daylight hours in the year, a climate-based simulation would output approximately 4,380 values for every calculation point considered, and potentially several times this number if the simulations were run at a shorter time-step to, say, better resolve the progression of the solar patch across the internal space.

Various climate-based daylight metrics have been formulated since the emergence of climate-based modeling in the late 1990s. As of 2010, these metrics are being investigated by daylighting researchers in order to determine their potential to reliably characterize daylight in buildings for the purpose of discriminating between "good," "bad," and "mediocre" designs [61, 68]. One of the more straightforward climate-based metrics is daylight autonomy (DA) [69]. The DA metric determines the annual occurrence (within, say, working hours) of illuminances above a stated design level illuminance, e.g., 300 or 500 lux. It is well known, however, that occupants prefer daylight illumination not to exceed certain levels, although it is not clear what precisely those levels are since occupants vary greatly in their responses. The "useful daylight illuminance" (UDI) metric was formulated as



Daylight, Indoor Illumination, and Human Behavior. Figure 20
Climate-based daylight modeling compared to daylight factor and snap-shot "clear sky" options. Luminous efficacy model* is used if the data contains irradiance only

a means to reduce the voluminous time-series data from a climate-based simulation to a form that is of comparative interpretative simplicity to the daylight factor method, but which nevertheless preserves a great deal of the significant information content of the illuminance time-series. The UDI metric informs on the occurrence of illuminances in the range that occupants either prefer or tolerate together with the propensity for excessive levels of daylight that are associated with occupant discomfort and unwanted solar gain [62]. Thus useful daylight illuminance is more firmly grounded on human factors than metrics which determine only sufficiency for task.

Achieved UDI is defined as the annual occurrence of illuminances across the workplane that are within a range considered "useful" by occupants. The range considered "useful" is based on a survey of reports of occupant preferences and behavior in daylit offices with user-operated shading devices. Daylight illuminances in the range 100–500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 500 to around 2,000 or maybe 3,000 lux are often perceived either as desirable or at least tolerable.

The range limits for UDI depend to a degree on the particular application, and, at the time of writing, there is no consensus on what precise values the upper and lower range limits should have. Nonetheless, the UDI scheme combines intuitive simplicity with rich information content. For the example shown below, UDI was defined as the annual occurrence of daylight illuminances that are between 100 and 3,000 lux. The UDI range is further subdivided into two ranges called UDI-supplementary and UDI-autonomous. UDI-supplementary gives the occurrence of daylight illuminances in the range 100–300 lux. For these levels of illuminance, additional artificial lighting *may* be needed to supplement the daylight for common tasks such as reading. UDI-autonomous gives the occurrence of daylight illuminances in the range 300–3,000 lux where additional artificial lighting will most likely not be needed. The UDI scheme is applied by determining at each calculation point the occurrence of daylight levels where:

- The illuminance is less than 100 lux, i.e., UDI "fell-short" (or UDI-f)
- The illuminance is greater than 100 lux and less than 300 lux, i.e., UDI supplementary (or UDI-s)
- The illuminance is greater than 300 lux and less than 3,000 lux, i.e., UDI autonomous (or UDI-a)
- The illuminance is greater than 3,000 lux, i.e., UDI exceeded (or UDI-e)

The same space that was used for the daylight factor example is employed again. Now, however, time-varying illuminances across the workplane during the hours of 09:00 to 18:00 were predicted for the entire year, i.e., a total of 3,285 h. Simulations were carried out for the space having, in turn, north- and south-facing glazing and the sun and sky conditions were derived from a standardized climate file for London, UK. For this illustration, there was no attempt to model user operation of blinds, etc.

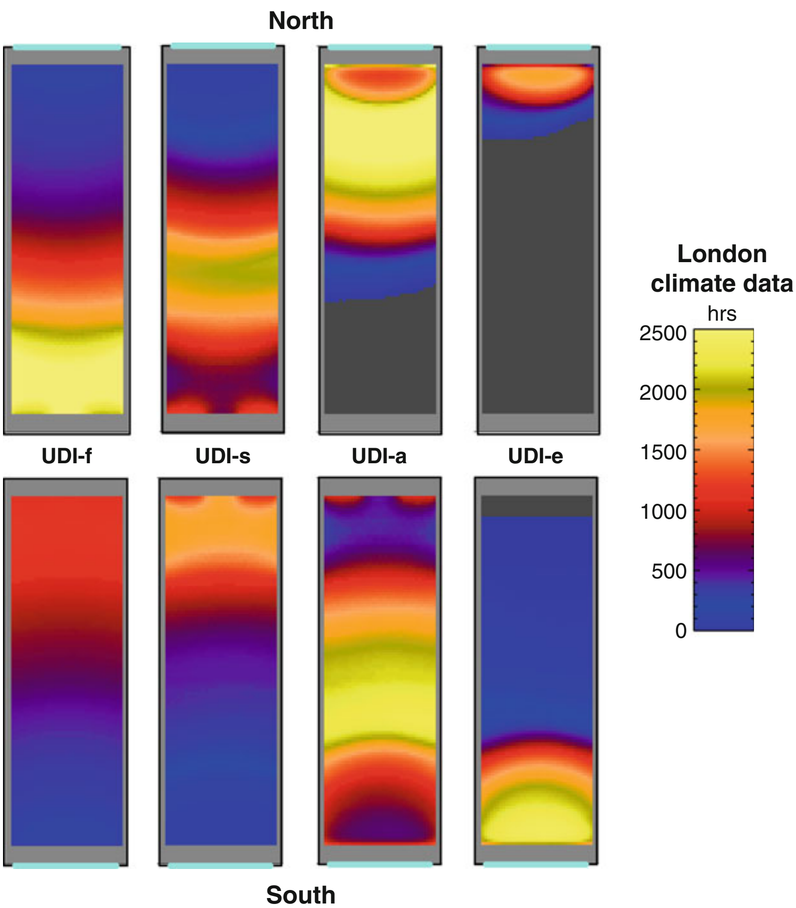
The four UDI metrics determined from the illuminance data for both orientations of the space are shown in Fig. 21. The occurrence of the various UDI metrics is shown using color, and a zero value for the metric is shaded dark gray. The light gray perimeter indicates the space between the work and the walls of the space. In these plots we can readily see the contribution that sunlight has to overall illumination of the space by comparing the north and south orientations. In the absence of target values for the various UDI metrics, the approach is most useful to the designer when, e.g., various facade options need to be compared. Those that maximize the UDI-a metric without undue occurrence of UDI-e are likely to offer the best daylighting design – though it needs to be acknowledged that this supposition will need to be tested and proven.

Although there is no consensus yet on the type of climate-based daylight metric (e.g., UDI and DA) that should feature in future guidelines [68], there is a groundswell of opinion that the half-century-old basis of daylight evaluation needs to be updated. In the meantime, climate-based modeling has made the transition from research to practice and is increasingly used by consulting engineers in their striving to achieve that elusive goal of the well-tempered daylit environment.

Metrics founded on climate-based daylight modeling will be the key to reliable evaluation of designs for well-daylit low-energy buildings. There remains, however, some work to ensure that future daylighting metrics will act in concert with other metrics, e.g., for thermal performance, and so not give conflicting guidance to the building designer.

Advanced Glazing Systems and Materials

The use of daylight in office buildings is generally considered to be a greatly underexploited resource. In large part this is because of both the highly variable nature of daylight illumination and its prevailing direction as it enters a space. Variability in daylight means that users will often need to use shades at least some of the time to moderate excessive ingress of daylight. Daylight illumination from perimeter glazing enters a space with a predominant downward direction. Those work areas close to the window may receive plentiful daylight; however, much of the natural light will arrive at the floor where it will be mostly absorbed due to the typically low reflectances of flooring materials. What little light there is reflected up from the



Daylight, Indoor Illumination, and Human Behavior. Figure 21
Annual occurrence of UDI metrics between the hours of 09:00 and 18:00 for north and south orientations (London, UK, climate data)

floor may encounter significant obstructions (e.g., desk, chairs) before having the possibility of being reflected again – now downward off the ceiling – to contribute to illumination on the workplane. In short, reflection of light from the floor to help illuminate the space is a low efficiency process with limited effectiveness. Another key issue with traditional building facades that also serves to greatly impair the potential daylighting performance of a space is the design and user operation of the shading systems, e.g., venetian blinds, etc. Many shading systems act as a "shutter" that is either open or closed, with users rarely making the effort to optimize the shading for both daylight provision and solar/glare control. Furthermore, blinds are often left closed long after the external condition has changed. The exploitation of daylight in buildings, particularly those dominated by side-lighting from vertical windows, could be greatly improved by any of the following:

1. Redirecting the daylight that enters the space toward the ceiling and walls where subsequent reflections will help to better distribute the daylight deeper into a space
2. For a shading system, modulating the daylight gradually rather than an on/off shutter operation
3. Reducing, possibly even eliminating, the need for user interventions, e.g., the lowering of blinds

The purpose of the majority of so-called advanced glazing systems or materials (AGSM) is to improve overall daylighting in a space by achieving one or more of the above-mentioned goals.

AGSMs fall into to two broad categories: active and passive. Active systems vary some property (e.g., visible light transmittance) automatically according to some control parameter (e.g., illumination at the workplane), though they may often include an option for user override. A passive system is one that is invariably fixed requiring no external control either automatic or manual. However, some of the passive systems described below could have, say, automated movement though this would add considerably to the cost. Any of the systems discussed below will be subject to the same issues regarding visual quality (i.e., providing adequate views, avoiding glare, etc.) that are a consideration for conventional glazing.

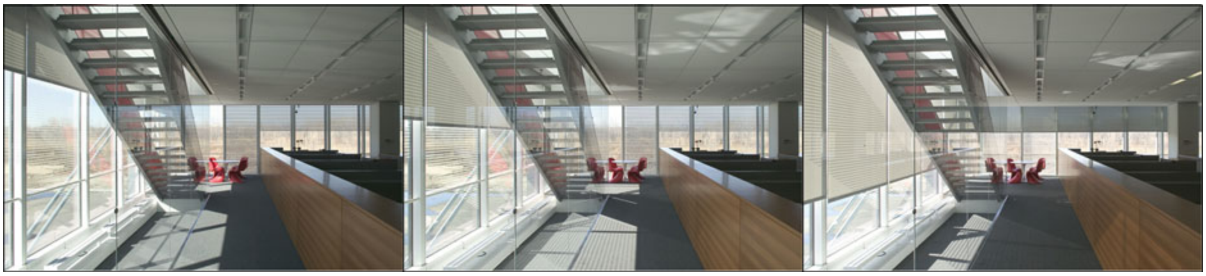
Passive AGSMs The goal of most of the passive systems is to redirect daylight in some fashion, and any changes in the magnitude and distribution of the transmitted light is due to variation in the amount and direction of the incoming light. Passive AGSMs are usually in the form of a material applied to one of the glass surfaces of a window, or are themselves a glazing element, e.g., one part of a double glazing system where the other might be standard glass. The light redirection can be achieved by manipulating the specular and/or diffuse transmission properties of the material. Glazing systems in this category include light redirecting prismatic panels, laser-cut panels, diffusing materials, mirrored louvers, etc. Some of these materials have been available since the 1980s; however, the uptake has not been great. In part this is due to either limited long-term performance data [70] and/or the inability to predict their daylighting performance at the design stage due to insufficient knowledge of the material's light transmission properties [71].

Anecdotal reports from some early installations of prismatic glazing suggests that the lack of a clear view to the outside together with secondary effects such as dispersion have not found favor with building occupants. More recent innovations have attempted to address these issues. The specular redirecting material marketed as Serraglaze provides a relatively clear view for an observer at normal incidence, but effectively blocks direct transmission of high-angle sun by redirecting it up toward the ceiling. Translucent materials such as Kalwall have very low thermal conductivity and can be used to replace sections of wall as well as glazing. However, these materials are essentially diffusing panels and so must be used in conjunction with clear glazing to provide views of the outside.

A common addition to windows to moderate both the solar gain and the daylight ingress is a film to reduce the overall transmissivity of the glazing. These films vary greatly in visible transmittance (from around 0.6 down to 0.1) and may have a pronounced color hue. Even films with the lowest transmittance usually need additional shading to moderate direct sun. The reduced transmittance of windows with films can, for the occupants, make views to the outside appear drab and gloomy, particularly on overcast days. A new approach to tempering daylight which, like films, can be applied as a retrofit is a novel treatment called Solaveil [72]. This material is fabricated using digital printing techniques which deposit microscale 3D structures on the substrate which act both as a "glare filter" and a redirecting "micro-light shelf." Before and after photographs for a retrofit installation of Solaveil are given in Fig. 22. The "before" image on the left shows how the building was typically used prior to the retrofit: the blinds are down to control glare and direct sun, and the electric lights are switched on. The "after" image on the right shows the treated area of the window which now acts as a diffusing light shelf redirecting light to the ceiling and protecting occupants from harsh, direct sun. Note that no additional shading has been installed and the lights – now photoelectrically controlled – are switched off. The lower untreated part of the window provides occupants with views to the outside. Initial findings indicate a significant potential for saving energy in both lighting and cooling from such interventions.

Active AGSMs The most established of the technologies in this category is the automated shading system where, say a motorized roller blind is deployed incrementally according to some sensor input, e.g., measured daylight level. This shading system features in the facade design throughout the majority of the 52 floors of the New York Times Building [73]. The design goals for the shading system were to

Daylight, Indoor Illumination, and Human Behavior. Figure 22
Photographs showing before and after cases where the standard glazing with blinds was replaced with a novel window treatment called Solaveil (Photos courtesy Solaveil)



Daylight, Indoor Illumination, and Human Behavior. Figure 23
Sequence showing deployment of shades in a full-size mock-up of New York Times Building offices (Photos courtesy LBNL)

- Maximize natural light
- Maximize occupant connectivity with the outdoors, i.e., external views
- Intercept sunlight penetration so as to avoid direct solar radiation on the occupants
- Maintain a glare-free environment
- Provide occupant manual override capability

The overall intent was to keep the shades up as much of the time as possible without causing thermal or visual discomfort. Thermal comfort is assured by solar tracking and the geometry of the external sun screens. Visual comfort is attained by managing the luminance on the window wall so that it does not exceed certain threshold values. A manual override system was specified because previous post occupancy evaluations of automated shade systems indicated that occupants were likely to complain if a manual override was not provided. A sequence of photographs showing incremental deployment of the shades is given in Fig. 23. Although a formal post-occupancy evaluation of the New York Times Building has yet to be carried out, anecdotal evidence from informal surveys indicates a high level of user satisfaction with the daylighting systems. Furthermore, effective daylighting has significantly reduced the energy consumed for artificial lighting. The NYT daylighting system provides a degree of modulation for the shading (they are deployed by increments) and has greatly reduced the need for user interventions.

In contrast to using standard shade materials deployed either manually or automatically, a glazing with a transmissivity that varies continuously between

Daylight, Indoor Illumination, and Human Behavior. Figure 24
Images showing electrochromic glazing in clear and darkened state (Photos courtesy SAGE Electrochromics)

clear and dark extremes would offer a much greater degree of control over the luminous environment. Indeed, the dynamic control of daylight has been termed the "Holy Grail of the fenestration industry" [74]. In principle, the approach is simple: the transmission properties of the glazing are varied to achieve the best possible luminous environment. Formulations based on electrochromic (EC) principles, where the glazing transmission is modulated by a small applied voltage, are considered the most promising at present. In practice, the formulation and production of commercial-sized EC glazing has proved a formidable task. Recently, however, a number of technical hurdles have been overcome, preproduction samples of EC glazing have been deployed in test facilities for evaluation [75] and commercial installations have followed, Fig. 24. The optical properties of EC windows can be modulated using control variables such as incident or transmitted solar radiation, daylight illuminance, ambient air temperature, or space thermal load [76]. In the clear state the visible transmittance of EC glazing can be as high as 60%. However, to avoid the need for any additional shading (e.g., by venetian blinds), the visible transmittance in its tinted state has to be as low as 2%. This has now been achieved in production samples and, as prices fall, it is to be expected that EC glazings will become a more mainstream product.

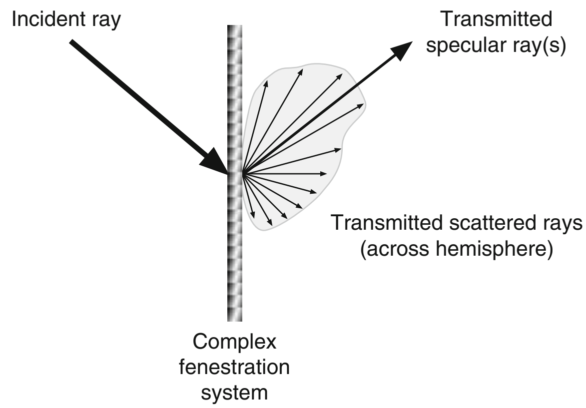
In addition to the electrochromic method, there are also formulations for light modulating glazing where the visible transmittance varies autonomously in response to either the temperature of the material or the intensity of incident illumination, known as thermotropic and phototropic respectively. The phototropic glazings have a formulation which is similar to that commonly used in "reactive" sunglasses, whereas thermotropic glass consists of two panes of glass sandwiching a polymer gel that undergoes a transition from clear to cloudy at a threshold temperature [77]. These autonomous systems are largely confined to research studies at present, and the inability to control their transmission properties depending on some internally measured quantity, e.g., daylight levels, may ultimately prove to be a drawback rather than an advantage.

Evaluating AGSMs Advanced glazing systems/materials have the potential to enhance the daylighting performance of a space. Performance, cost, and user acceptance are key factors which determine the overall effectiveness of an installation. The first two of these factors can, in principle, be determined using simulation – the predicted performance could be judged against likely cost. It may even be possible to employ simulation to anticipate to some degree user acceptance of a novel glazing system/material, though the evaluation would have to be founded data from occupant-based studies to have credibility.

To simulate the performance of an advanced glazing system/material can be quite challenging due to their particular optical properties which often diverge greatly from standard glazing. The optical properties of ordinary clear glazing and reflective materials that have a matt finish are relatively easy to characterize for the purpose of lighting simulation. Less straightforward materials such as coated glazings and materials that produce part specular reflections are more challenging to both characterize and also to model accurately in a simulation. Tools such as Optics 5 and Window 6 can assist the creation of the necessary material description files for multilayer coated glazings [78]. The highlights resulting from even tiny specular reflections are an important part of the overall visual impression of a daylit space; however, the total light energy resulting from these reflections is usually very small and can be ignored when predicting illuminance quantities. Specular reflections are only important for overall light transfer in a space when significant amounts of the entrant direct and diffuse light are reflected, e.g., when a mirror light shelf is present. Large-scale reflecting/redirecting features such as light shelves or "skylight" wells can be modeled using standard *Radiance.*

A major issue with advanced glazing systems/materials however is that there is usually no straightforward relation between incident and transmitted light that can be determined a priori from simple, e.g., analytical, methods. Thus the optical properties of the AGSM need to be determined from either comprehensive measurements or, alternatively, simulation. For each light ray incident on an AGSM, there may be one or more strongly transmitted rays – which may be redirected in some fashion – together with, in most cases, a unique distribution of semi-diffuse or scattered light, Fig. 25. Thus, to fully characterize the material, the distribution in luminous output across the full hemisphere of transmitted rays needs to be determined for every incident direction [79]. This is the bidirectional transmission distribution function or BTDF [80]. The BTDF is challenging to characterize even for seemingly simple materials such as translucent glazing [81]. Another approach to characterization of the BTDF is to predict it by simulation rather than by measuring it directly [82]. For this approach, the geometric microstructure of the material needs to be specified to a high degree of precision and the BTDF predicted using a forward ray-tracing program.

It is possible to model some AGSMs without going to the lengths of determining the full BTDF if the transmission properties of the materials can be adequately represented by an analytical function. This has been achieved for certain types of laser cut panels [83] and the redirecting material Serraglaze [84]. A limited set of angular-dependent transmission measurements will still need to be taken to calibrate the analytical model.

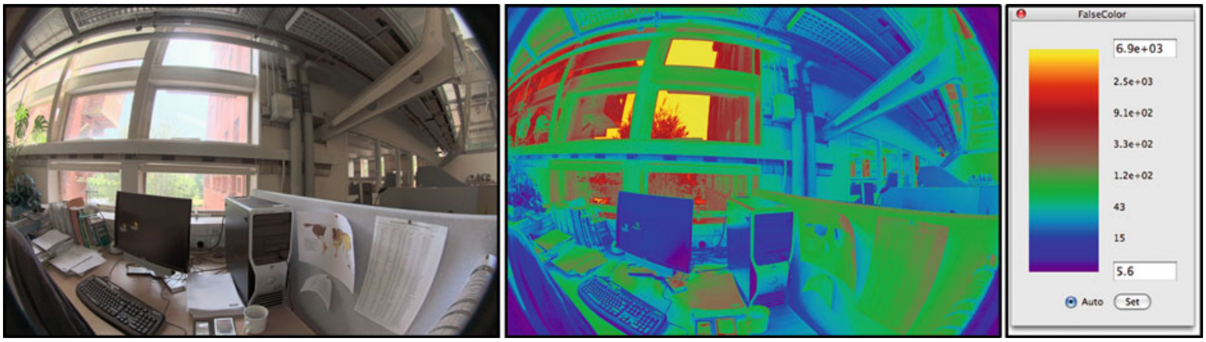


Daylight, Indoor Illumination, and Human Behavior. Figure 25
Schematic showing the distribution in transmitted light from a complex fenestration system

Note that although there are various approximations to model the light transmission through venetian blinds, even these commonplace devices have complex optical properties. Both the slat angle and the coverage of venetian blinds can be varied continuously and independently of each other. For any given sun position, either of these factors has a considerable effect on the overall light transmission, i.e., the BTDF [85]. Venetian blinds therefore can be more difficult to model accurately than many of the "advanced" systems/materials because their BTDF is dependent on the user operation.

Light-pipes (i.e., tubular daylighting devices) offer a potentially effective daylighting strategy for low-rise buildings. The performance of a light-pipe can be estimated using analytical methods or relatively simple software tools [86, 87]. The detailed simulation of light-pipe performance however remains quite challenging.

Characterization of BTDFs by either measurement or prediction is a highly specialized task, as is the use of these complex transmittance data in lighting simulations. There is considerable research to be carried out at



Daylight, Indoor Illumination, and Human Behavior. Figure 26
High dynamic range image used to measure the luminance of the occupants field of view

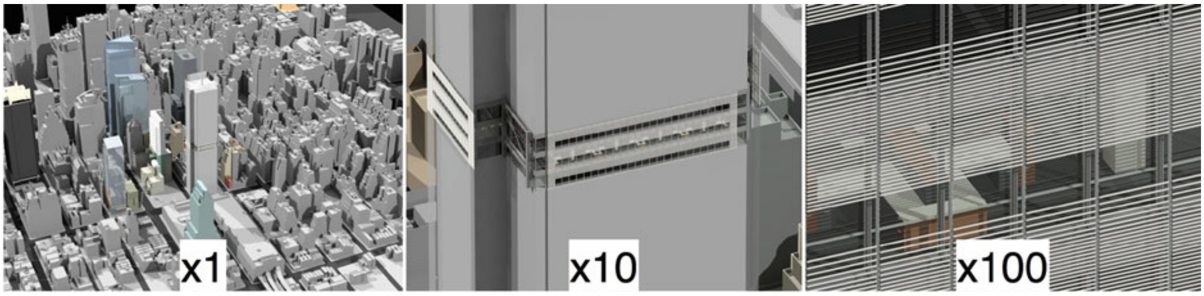
all stages from characterization to implementation in a software tool before their use in lighting simulation becomes commonplace. The development of libraries of BTDF databases for various products, based on standardized test procedures, will be necessary to enable full utilization of these products in design optimization studies.

New Approaches to Measuring the Daylit Environment

Quantitative knowledge of the internal daylit environment has, until recently, been largely restricted to measurements of illuminance (typically at the workplane) and "spot" measurements of luminance taken by a narrow (e.g., 1°) field-of-view photometer. Illuminance at the workplane is rarely recorded over long periods in an occupied building due to the cost of the monitoring and the disruption caused by wires, etc. (though there are now largely autonomous wireless sensors available, albeit at a high cost). Humans have an almost 180° forward-facing field of view, so a measurement taken using a "spot" photometer with a 1° field-of-view records only a very small part of what is seen.

As noted in an earlier section, understanding of visual comfort in daylit environments is lacking in part because we have scant empirical data on the (constantly changing) visual field. A recent technology called high dynamic range (HDR) imaging has greatly expanded our capacity to measure and describe the visual field. An HDR image is one where every pixel contains a luminance reading for that point in the recorded scene, in other words: a measurement of luminance. There are a small number of specialist HDR cameras on the market; however, it is possible to create HDR images from multiple exposures taken by consumer digital cameras which can have up to 10 million or more pixels [88]. Furthermore, the consumer cameras can be fitted with a full fish-eye lens so the recorded image will be equivalent to or exceed the human field of view.

HDR image capture has been used in a number of daylight glare studies [89, 90] and also more generally to investigate lighting preferences in office spaces [91]. An example HDR image alongside a standard digital photograph is shown in Fig. 26. The view is of a workstation close to a window and with direct view of the sky. From the false-color HDR image it can be seen that the luminance of the sky is of the order of 7,000 cd m^{-2}. HDR imaging techniques were used to calibrate and commission the dynamic shading systems of the New York Times Building [73]. A key consideration in the design of the control system for the automated shades was to allow in as much daylight as possible without exceeding visual comfort criteria based on field-of-view (i.e., perceived) luminance. This was tested by measurement in the full-size mock-up of offices (Fig. 23) and evaluated more generally for the building using simulation (i.e., climate-based daylight modeling). The mock-up allowed only for limited scenarios, i.e., just two view directions with fixed external obstruction. The simulation, however, allowed multiple floors of the building to be evaluated in context (i.e., the surrounding buildings) and for all possible view directions. The images in Fig. 27 show long, medium, and close-up views of the



Daylight, Indoor Illumination, and Human Behavior. Figure 27
Highly detailed 3D model of the New York Times Building and surrounding Manhattan – full office detail modeled for floor 26

highly detailed 3D model used for the simulation – model detail of the offices was generated on a per-floor basis for each of the floors evaluated.

High dynamic range imaging technology may become sufficiently compact and inexpensive to replace the traditional sensors that are currently used with daylight-responsive systems, e.g., photocell-controlled artificial lighting, automated shades/blinds and the transmission of electrochromic glazing [92].

Daylight and Saving Energy

It seems to be generally believed that "good" daylighting design will lead to reductions in electric lighting consumption, and also overall energy consumption. This belief results in part from common-sense notions and the pioneering work of Crisp and Hunt in the 1970s [93, 94]. The potential for energy savings was usually based on extrapolating internal illuminance from daylight factors and cumulative daylight distributions, and then applying some model of lighting control [95]. Lighting control models based on manual switching were derived from observed patterns of behavior [57, 96]. It was realized early on that occupant control alone was unlikely to lead to significant energy savings for the simple reason that lights were likely to remain switched on even when there was plentiful daylight. Some form of timed switching and/or automatic control was needed to ensure energy savings, and a number of largely theoretical formulations for occupancy-sensor and photoelectric control of lighting were devised [93]. The design and artificial lighting of nondomestic spaces has changed considerably over the last 30 years, and some of the findings noted in occupancy studies carried out three or more decades ago may not necessarily hold today.

Post-occupancy studies carried out in real buildings have shown that the actual energy performance is invariably markedly worse than that predicted at the design stage. The landmark PROBE study determined many of the reasons for this [97]. Some of the findings specific to lighting controls are noted below:

- Default states which are non-optimal, but cause the least trouble for occupants and management. The most common of these is blinds closed lights on, which has undermined many a daylight and lighting control strategy.

  Photocells used for perimeter dimming . . . were also confused by light redirected upwards onto them from the venetian blind slats, requiring control setpoints to be raised, so reducing the benefits of daylight-linked dimming.

The ratio of predicted to realized energy savings is defined as the "realized savings ratio" or RSR. Studies of automatic photocontrol performance in the USA have shown very high RSRs for simple top-lit spaces, and much lower RSRs for more complex side-lit spaces [98]. Predicting the performance of an automated lighting control system is a function of many factors, including not only space design and daylight availability, but also lighting system design, control settings, commissioning history, and occupant override behavior.

Daylight is merely the visible part of the radiant energy that enters through windows. Furthermore, the bulk of the daylight energy that enters a space is converted into thermal energy after just a few reflections. Many office buildings in moderate climates now have air-conditioning largely due to the high internal gains. In warmer climates cooling may be needed for large parts of the year. When cooling is needed in a space, both the use of electric lighting and the ingress of daylight will each add to the cooling load.

Attempts to provide good daylighting could therefore lead to a net *increase* in energy consumption if the additional cooling load due to daylight (i.e., including the solar component) exceeds the energy saved due to reduced electric lighting, or if the net heat gains and losses through the fenestration do not compensate for the lighting energy saved. In fact, an all too common scenario in over-glazed buildings is where the blinds are down to control glare and the lights are left on. This leads to the undesirable combination of high solar gains (blinds reject only a small part of the energy once it has passed through the glazing) and no "daylight benefit" in terms of displaced lighting energy or daylight provision. A full consideration of the potential for daylighting to save energy should, at some point, account also for the thermal effects of daylight. In which case, daylight metrics will need to be calibrated against criteria for whole building energy use and not just the potential to reduce the energy consumed for electric lighting. That was not a possibility with the standard daylight factor approach because the sun did not figure in the evaluation. However, with the emergence of climate-based daylight modeling, a truly holistic evaluative schema which can be applied at the design stage is now a likely prospect.

Good daylighting alone is unlikely to save energy unless it is part of an integrated design scheme. The typical lighting power densities (LPDs) in office spaces range from about 12–20 W/m^2, with those at the lower end considered "good practice." It is possible however to achieve LPDs significantly lower than the good practice value – without recourse to emerging technologies such as light emitting diodes – using only good-quality low-energy fluorescent lights. This was successfully demonstrated in the New York Times Building which has an LPD of only 4.26 W/m^2.

A fully integrated low-energy daylighting design must necessarily be tailored to the local environment, in terms of both the climate and the surrounding built context. It is hoped that a new generation of daylight metrics founded on climate-based modeling will help designers to achieve that elusive balance between daylight provision and effective solar protection. And, importantly, offer design guidance that does not conflict with other criteria such as thermal performance of the building.

The potential for new technologies (e.g., electrochromic glazing) to save energy can only be reliably assessed using climate-based daylight modeling. Building facades may become electricity generators through the widespread adoption of various building-integrated photovoltaic (PV) technologies [99]. Semitransparent (PV) panels could serve as combined widows and electricity generators [100]. Thus daylight consideration could become closely linked with other performance aspects of the overall building.

Future Directions

Both the theoretical basis for and the practical application of daylighting in buildings are in the midst of a fundamental reappraisal. The emergence of findings that relate daylight exposure to positive outcomes in terms of productivity, health, and well-being have led to a renewed focus on daylighting in buildings. Throughout the developed world, governments and regulatory bodies are encouraging the adoption of design guides and recommendations in the hope that reduced energy consumption in buildings can be achieved, in part, through effective daylighting design. The theoretical basis for these guidelines, however, is a crude representation of actually occurring daylight conditions. A more realistic evaluative scheme has emerged with the development of climate-based daylight modeling, which it is widely believed will soon replace the daylight factor as the basis of a new generation of daylighting guidelines. A large number of advanced glazing systems and materials for enhancing the daylight in buildings have recently appeared on the market, and there are new formulations in the early stages of development. Market penetration of innovative daylighting systems has, until now, proven to be difficult because the standard "measure" of performance (i.e., the daylight factor) gives no indication of how much natural light and how often. Data on the magnitude and occurrence of absolute measures of natural illumination – precisely how much and how often – are vital to reliably assess both the performance-effectiveness and the cost-effectiveness of daylighting systems. Thus the hoped-for emergence of climate-based daylight metrics will greatly assist in the evaluation of these daylighting systems, and, for those shown to be effective, their marketing. Another consideration is the advances in measurement and control through techniques such as high dynamic range imaging. These theoretical and technological advances have the potential to radically improve our perception of what constitutes good daylighting in buildings, both in terms of basic design parameters and the use of novel glazing materials, thus paving the way for daylighting guidelines and codes that lead to the reliable and robust production of truly healthy, low-energy buildings.

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Daylighting Controls, Performance and Global Impacts

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Article Outline

Glossary

Brightness contrast/glare Risks of glare in daylighting

- Direct glare: sun is in user's immediate field of vision
- Background glare: brightness contrast between monitor and monitor background
- Reflected glare: mirroring effect on monitor surface

Daylight autonomy Daylight autonomy of a workplace is the percentage of normal working time without the requirement of electric lighting – i.e., the time in which the target illuminance can be maintained by daylight alone. This varies depending on the minimum illuminance required and is determined using daylight coefficient.

Direct/diffuse light Diffuse light illuminates a room or area contrast or shadow reduced. It is usually caused by extensive light sources like the overcast sky (5,000–20,000 cd/m^2). In contrast the clear sky has a luminance of up to 50,000 cd/m^2 which is caused by the high illuminance of the direct sun (100,000 lx).

Efficiency of daylight Depending on the type of building, 20–40% of its total energy requirement is used merely for electric lighting, primarily during the day. Using optimized daylight redirection systems, electric lighting demands can be reduced to less than 10% of total energy loads.

Heat gain from daylight versus electric light Outside, daylight produces up to 120 lm/W of energy. Inside – behind glass with controlled solar heat gain coefficients (SHGC) – daylight offers even greater 240 lm/W. Fluorescent luminaires, on the other hand, can only achieve approximately 70 lm/W, requiring much higher energy use per unit of lighting provided. As a result, the heat gain in buildings using daylight is less than 1/3 of the heat generated by electric lighting, a gain taken into account in the energy balance of a building through the SHGC value.

Illuminance (lux/lumen/candela) Basic terms of lighting technology are:

- Illuminance E [lx]. The total luminous flux incident on a surface per illuminated surface area
- Luminous flux Φ [lm]. The radiated power emitted by a light source or the radiated power incidence on a surface
- Luminous intensity I [cd]. The directional luminous flux of a light source

Light distribution curves (LDC) Light distribution curves of daylight systems indicate the direction and the intensity of the light distribution. Given the sun's changing angles of incidence outside, factors to be considered in mapping the light distribution inside include light redirection elements and the potential for adjusted tilt angles to ensure freedom from glare.

Quality assurance for daylight control Quality assurance must ensure the simultaneity of three criteria:

- Reduction of solar irradiation in summer (F_c value) for passive cooling balanced by solar gain in winter
- Sufficient daylight supply on the task surfaces (daylight coefficient)/visual comfort
- Sufficient visual transmission for quality views

Conventional louvers are generally closed to protect against glare and overheating. This not only hinders the view outside, but also prevents sufficient daylight from coming in. Design for daylight, including light redirecting louvers, ensures simultaneity of all three qualities.

Reflectors – contoured prismatic, mirror and diffusing blinds Basic functions of mirror or prismatic light redirecting louvers include reflection of the

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light back to its source to protect against overheating (thermal comfort) and/or redirection of daylight into the space to improve the illumination in the room (visual comfort). Precise contours make it possible to calculate exactly the quantitative light distribution (both inside and outside) with reference to the louvers' tilt angle and the altitude of the sun. Mono-reflective light control refers to the redirection of light inside and its deflection back outside in a single reflection in order to minimize its absorption by the blinds and any resulting heat development. Mono-reflective light control is required to prevent undirected reflection of the rays back and forth between louvers to prevent unplanned light scattering or absorption.

Shading for passive cooling balanced by passive solar heating Shading is a critical protective function against overheating to avoid active cooling, achieved exclusively through reflection of solar irradiation. At the same time, "passive solar heating" relies on solar transparency to achieve high levels of solar gain to reduce mechanical heating requirements. To avoid the risk of overheating in summer, it is critical to provide seasonally or daily dynamic devices that balance light and heat gain.

Total solar energy transmission (g/SHGC) Total solar energy transmission through the glazed area (g-value, SHGC) defines the heat load resulting from solar irradiation, light transmission, and secondary heat radiation ($g = \tau_{verg} + q_i$). Design decisions include the total energy transmission for the window assembly and its interior and exterior layers that form an overall system including sun and light control. The F_c value for the system indicates the percentage by which the total energy transmission through the glazing is reduced through redirection of the light: $F_c = g_{tot}/g_{glazing}$.

Definition of the Subject

Worldwide, efforts are made to introduce energy saving regulations and laws requiring the use of regenerative energies. The focus so far has been on energy conversion systems to obtain power and heat. Yet, daylight is one of the most substantive renewable energies, and highly underutilized in buildings. It should be obvious that using the sun for natural illumination of indoor environments, without overheating, should be a primary goal for the building sector.

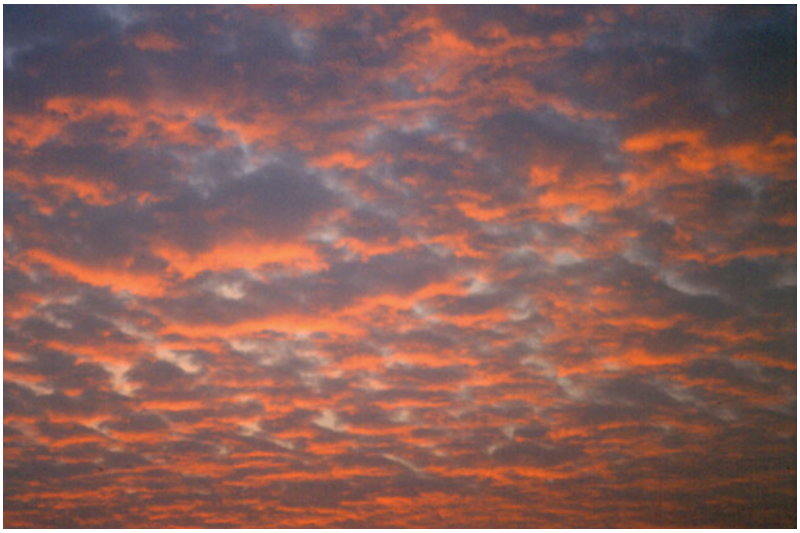
Improving the supply of natural daylight in workplaces rather than using electric lighting is a highly sustainable and economic resource that saves both energy and power. Over 30% of the total energy consumption of average buildings is used for electric lighting, and most of this during the daytime! Simply by redirecting daylight into the room, the use of electric lighting can be reduced by at least 50%, and effective shading with daylight offers further cooling energy savings. Daylight management systems are thus the focal point of the latest strategies to save energy and reduce the carbon footprint of buildings.

This entry outlines the critical characteristics of daylighting design, incorporating reflection, redirection, and diffusion in the design of façades and their external and internal layers. The correct manipulation and exploitation of the sun and daylight is vital as an energy savings resource and must mature into a key element in the development of energy concepts. Daylight design must become central to a range of disciplines, including lighting technology, façade technology, energy technology and architecture, and ultimately calls for integrated design studies to provide training in planning and coordinating between the various disciplines.

Introduction: What Is Daylight?

Common parlance and building physics define "daylight" as follows: Daylight is perceived as brightness outdoors and includes all variants from twilight to the brightest time of day when the sun is highest, ranging from diffuse light in shaded areas or with cloudy skies to direct sunlight. The sun is the primary source of all variants of daylight (Photo 1).

Solar radiation is approximately 1 kW/m^2 on the earth's surface. The illuminance from direct sunlight is approximately 100,000 lx. A clear, blue sky has approximately 50,000 cd/m^2, a cloudy sky may have less or more – depending on the time of year – between 5,000 and 15,000–20,000 cd/m^2 [17].



Daylighting Controls, Performance and Global Impacts. Photo 1
Daylight is an experience of color, season, and daytime and helps human beings to reintegrate themselves into the cycles of nature

Depending on the location, daylight is in the wavelength range from 350 to 750 nm – roughly 40–50% of light radiation in the sensitivity range of our vision (Figs. 2, 3b–d, 6).

Whereas the term "daylight" more likely conjures up an image of diffuse light without directional reference – i.e., uniform light distribution from all directions – the sun itself has clear directional reference, which indicates to us the exact time of day and year (Fig. 1).

The number of daylight hours varies depending on latitude and time of year, and the number of sunny hours varies depending on the climate zone. Germany gets between 1,200 and 1,500 h of sunlight per year [5]. In many parts of California, the sun shines over 3,000 h [23] of approximately 4,300 daytime hours a year.

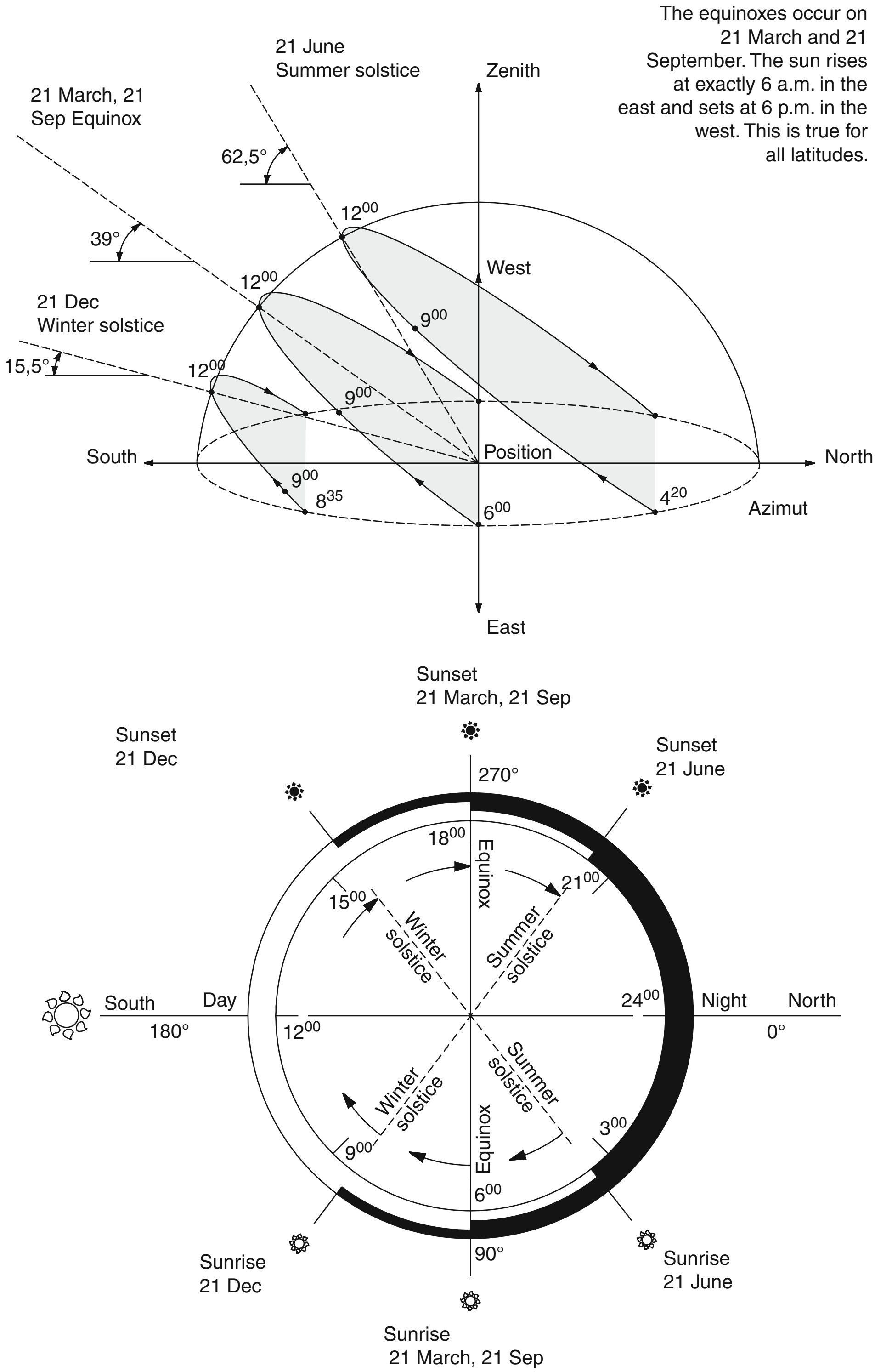
Design for daylight must address diffuse sky and sunny conditions, as they vary by orientation, season, and climate. Daylight design must address illuminance, glare, brightness contrast, and view content for visual quality in addition to managing solar heat gain for thermal quality.

Given the dynamic nature of daylight, light-transmitting building elements (windows and skylights) must be supported by "daylight technologies" to manage light transmission and redirection, balancing the variations in the sun's angles of incidence (Fig. 14) against variations in desirable heat energy transmission. The aim of daylight technologies is to achieve specific lighting effects using defined reflection, transmission, and/or absorption characteristics. Its further purpose is to gain more heat in winter and ensure shading for passive comfort in summer.

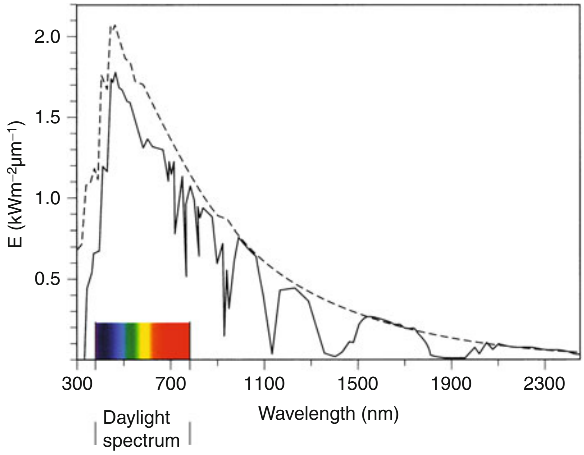
Effective daylighting design is dependent on the size of the windows relative to the proportion of the room, the configuration of the windows and their adjacent surfaces (to manage brightness contrast), the arrangement of windows relative to each other and the surfaces to be lit in the room (bi-directional and indirect light), the type of glazing (e.g., transparency, translucency, diffusion) including color effects (e.g., church windows) and the layers placed inside or outside of the glass that may change the transmission or directionality of the light.

Balancing Light and Heat: The Optimization of Daylighting

Current research and development in daylight-optimized glazing technologies concentrates on



Daylighting Controls, Performance and Global Impacts. Figure 1
Illustration of the daily and annual paths of the sun at 51° latitude [14]



Daylighting Controls, Performance and Global Impacts. Figure 2
Spectral energy distribution of daylight [9]

optimizing the energy transmission proportional to light transmission. Standard glazing, therefore, is defined on the basis of three physical reference parameters:

– Light transmission τ_L or $_{VT}$ (Fig. 3d)
– Total solar energy transmission or solar factor (g or SHGC) (Fig. 3a)
– Heat transmission coefficient U in W/m^2K (Fig. 3a)

Whereas τ_L and g are parameters related to the transmission of light and heat from the outside to the inside, the U-value is used to calculate the conductive heat losses from the inside to the outside. To maximize daylighting year round, while avoiding solar heat gain as cooling loads in summer, the τ_L and g-values (SHGC) will be critical (Fig. 3).

Thirty years ago, the visible light transmission (τ_L or $_{VT}$) of glass paralleled the heat transmission (SHGC or previously SC), with efforts to reduce heat transmission dominating specifications in an effort to minimize cooling loads. As a consequence, generations of dark or reflective glass buildings continue to be built, despite the fact that glazing innovations today allow for independent selection of visible transmission and shading values.

Typical glazing (6/16/6 and 4/12/4) of the latest developments has the following characteristics (Table 1).

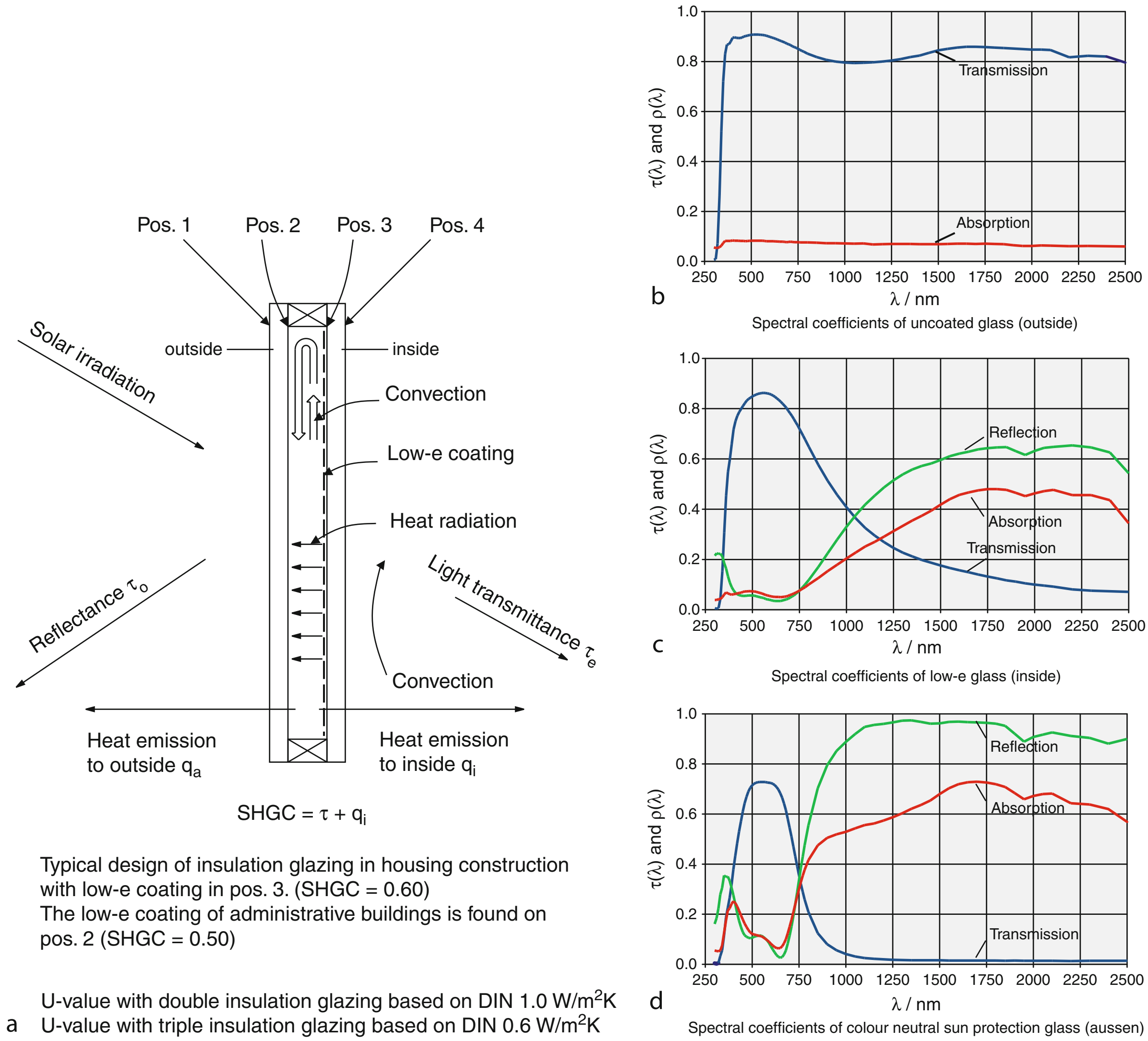
The most recent developments in selective coatings applied to glass surfaces use sputtering methods to allow a ratio of τ_L/SHGC of approximately 2 for insulated (double-glazed) glass units. These advances ensure a high level of light transmission τ_L while keeping the total energy transmission g (SHGC) to a minimum. The competition among glazing producers can be reduced to the following formula:

″More light, less heat″

In spirit, this formula is a vast improvement over less heat ergo less light – the reflective glass era. However, there are at least two other climate conditions that demand a more nuanced selection in glazing or glazing controls. First, climates that have high heating loads in both residential and commercial buildings will not benefit from low solar heat gain coefficient glazing materials. The potential for passive solar heat as a natural or renewable heating source is very significant (Table 1). In colder regions, it is best to use glazing with a high light and high total solar energy transmission to realize the additional solar gains in winter. Second, climates that are hot and sunny, with significant ground reflectivity, such as desert regions, have an additional challenge of managing both heat gain and brightness contrast, suggesting lower light and heat transmission glazing choices (Fig. 3d). Both of these climates will benefit from the lowest heat transmission coefficient possible (U-value) to reduce heat loss and heat gain (Fig. 4).

The highest level of natural conditioning through daylighting, shading, and passive solar heating can only be achieved through the addition of dynamic layers, either inside or outside the glazing, to allow for the exact amount of light and heat that is needed given time of day, season, orientation, and space function, in each climate.

The addition of dynamic layers becomes even more important as the design community pursues all glass buildings with floor to ceiling transparencies, regardless of the climate in which they are built. One only needs to see the latest buildings in Dubai, Hamburg, or New York to realize that façade design will need to resolve the transmission of daylight, solar heat and heat loss with dynamic layers, to enable natural energies to offset the major conditioning demands these façades have generated.



Daylighting Controls, Performance and Global Impacts. Figure 3
(**a**–**d**) Basics of building physics in daylight technology [12]

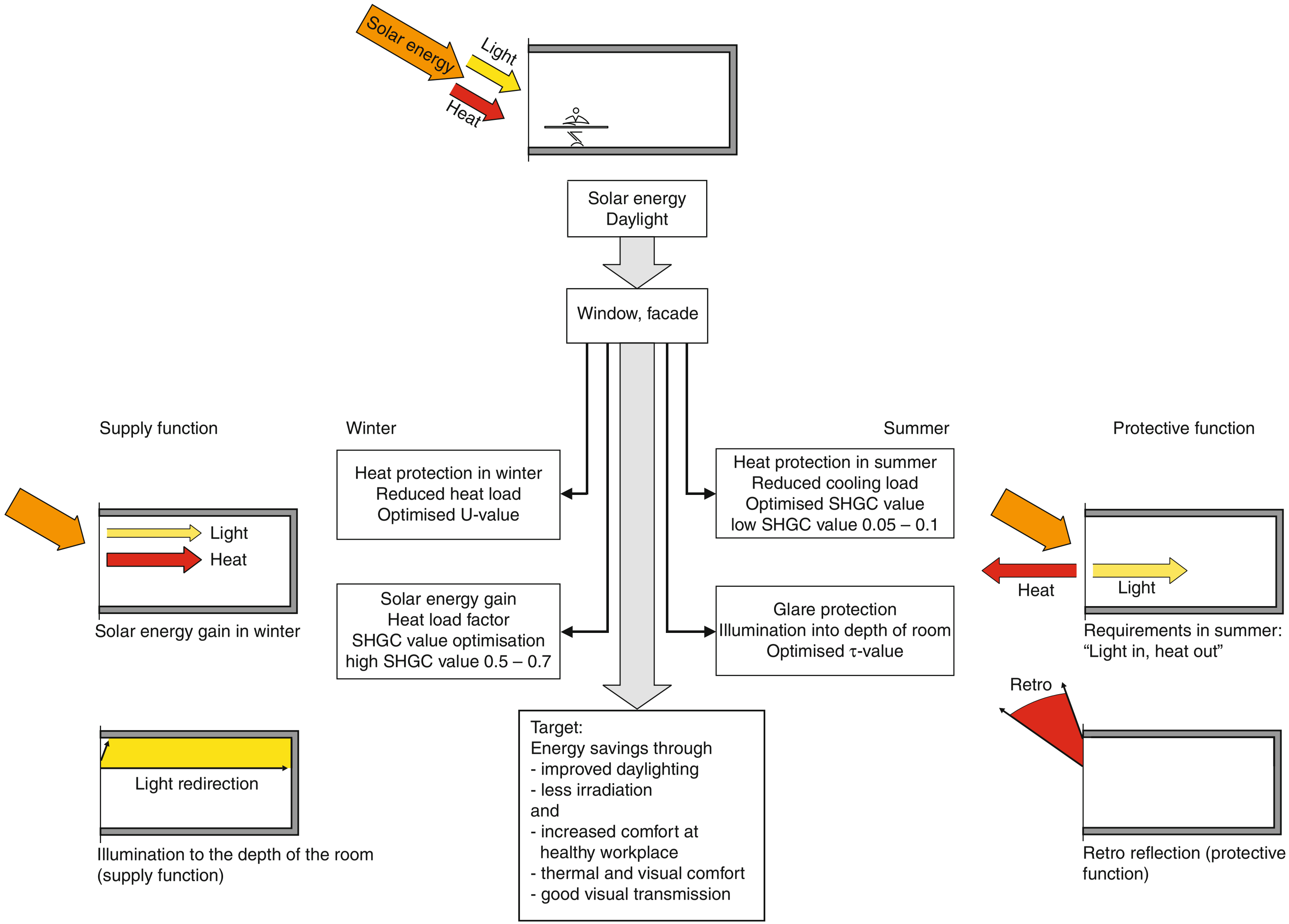
Daylighting Controls, Performance and Global Impacts. Table 1 Light to heat ratio [19]

	τ_L in %	SHGC in %
Sun protection glass	53	28
	61	44
	60	28
Low-e glass iplus 3LS	80	63
	78	61
	71	42

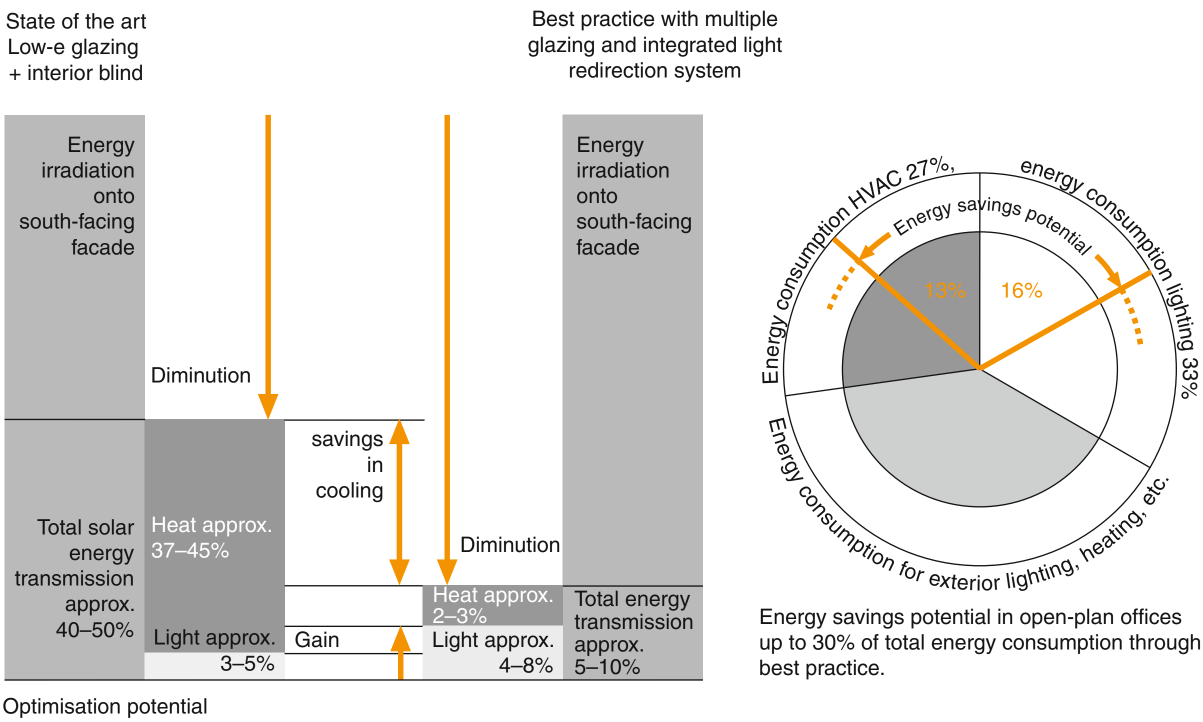
The Benefits of Daylighting: Energy, Health, and Design Flexibility

Energy Saving Potential of Daylighting

Electric lighting energy consumption [kWh] in conventional office buildings today is as much as 35% of the total electric load – demands that are generated primarily during the day when daylight is abundant [8]! Since the energy drawn for electric lighting is ultimately converted into heat, there is additionally



Daylighting Controls, Performance and Global Impacts. Figure 4
Tasks and functions of light-transmitting components in the conflict between required solar energy and passive cooling [14]



Daylighting Controls, Performance and Global Impacts. Figure 5
(**a**, **b**) Energy savings potential of a new, intelligent façade and daylight system in comparison to the state of the art

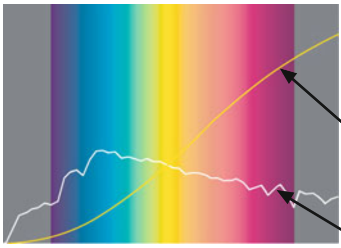
a load on the cooling system. Proportional to the total energy used, electric lighting can add as much as 16% to the cooling energy bill, such that the combined electricity costs for lighting and cooling are almost 50% of total electric demand (Fig. 5). While total energy consumption is made up of both electricity and fossil fuel energy uses, daylighting alone can reduce total energy use by as much as 25–30%, one of the most cost-effective investments for energy and carbon savings worldwide.

In the USA, where electric lighting is becoming pervasive during the daytime, the New Buildings Institute calculates that daylight harvesting systems can generate lighting energy savings of 35–60%. According to the US Department of Energy, daylight-response controls of skylights have demonstrated lighting energy savings in warehouses of 30–70%, without consideration of the additional cooling energy benefits. In a controlled experiment, the Energy Center of Wisconsin measured the additional cooling energy savings at 25% and fan energy savings at 3% (NBI, DOE, Wisconsin 2005).

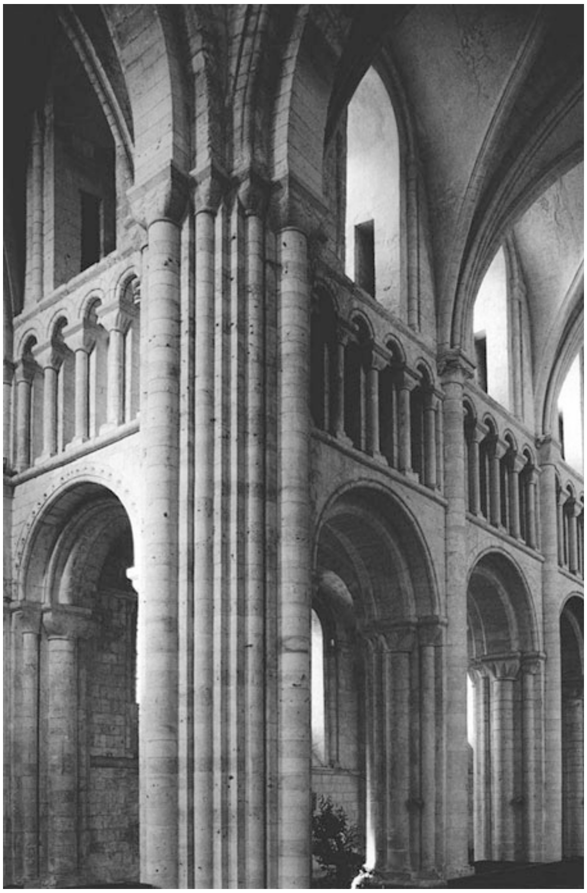
The economic impact of ignoring daylight is even more problematic because it is an electric load in buildings – for which source or primary energy costs are significant. One kilowatt of power on site uses approximately 3–4 kW of primary energy, with the rest lost as heat up the chimney at the power plant. In conventional coal or oil fired power plants, only 35–40% of the primary energy is converted into power with a further 6% of the energy produced at the power plant lost in transmission [21]. In developed economies such as the USA, Japan, and Germany, power plants are to be blamed for approximately 50% of all CO_2 emissions! Over 40% of each nation's total energy consumption in developed economies is used for heating, cooling, air conditioning, lighting, and other power requirements in buildings [11].

Daylight and Health

Humans, like plants, need to live and work in the full spectrum of light provided by [4] (Fig. 6). Daylight is critical for natural vitamin and hormone production,



Daylighting Controls, Performance and Global Impacts. Figure 6
Spectral distribution of daylight [18]



Daylighting Controls, Performance and Global Impacts. Photo 2
Examples from building history: Romanesque: interplay of wall relief and opening [14]

and is associated with numerous emotional values as well [9]. While the research on "daylight nutrient ingestion" through the human eye and the skin is still sparse, it is known that lethargy in winter and certain eating and hormonal disorders are due to a physiological lack of daylight [9]. These deficiency syndromes can be countered by using light treatments during which the patient stays, for hours, in "full-spectrum" settings for health.

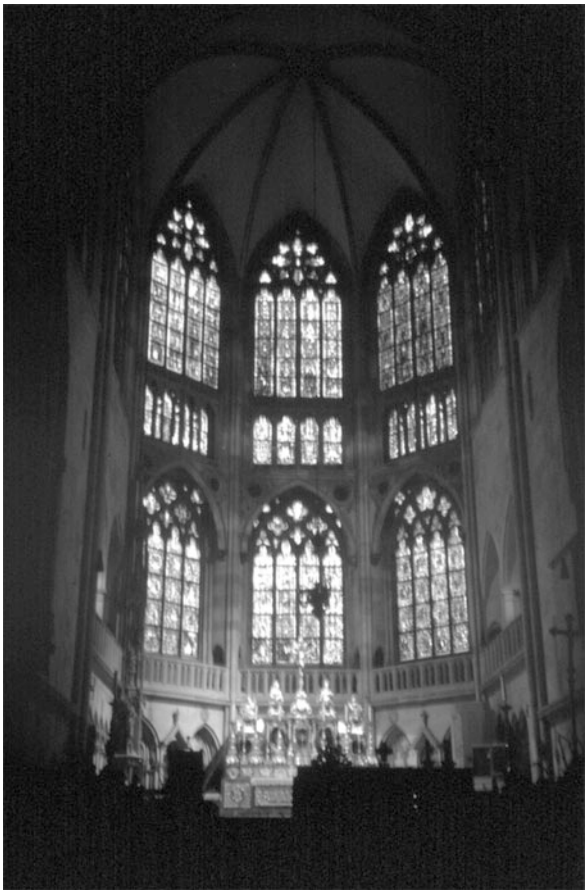
One quality of full spectrum daylighting that is significant is its color rendering index. For this reason, it is important not to distort the natural color–rendering qualities of daylight by tinted glazing or colored blinds, screens, and fabrics that change the color composition of natural daylight (Photo 8, Fig. 7). As a result, quality assurance must also take into account the color-rendering index of the daylight transmitted through the window and blind assembly (Fig. 7).

These findings call for "healthy" building design guidelines that ensure full "value-added" daylight to the occupants of the building, changing the color composition of the daylight as little as possible. It is not enough to simply provide sufficient lighting for a visual task; daylight designers must ensure that each individual receives the necessary light nutrition in their workplaces.

Daylighting and Design Flexibility

Effective daylighting design that manages cooling demands can also save building costs. The need for ceiling plenums are often driven by the demand for air conditioning, with air-based systems dominating the USA and now Asian building growth. The elimination of deep ceiling plenums for air-based cooling can save floor-to-floor heights, overall building height, and even associated elevator demands (Fig. 8).

Since managing solar heat and light can dramatically reduce cooling loads, the potential of radiant water-based cooling systems is unleashed. The use of water-based chilled ceilings, chilled beams, or radiant ceilings and walls for thermal cooling offers significant energy savings over air-based cooling [16]. In addition, the ducted systems can be dedicated to the delivery of fresh air, at 10% of the volume of air-based cooling



Daylighting Controls, Performance and Global Impacts. Photo 3
Examples from building history: Gothic: colored window [14]

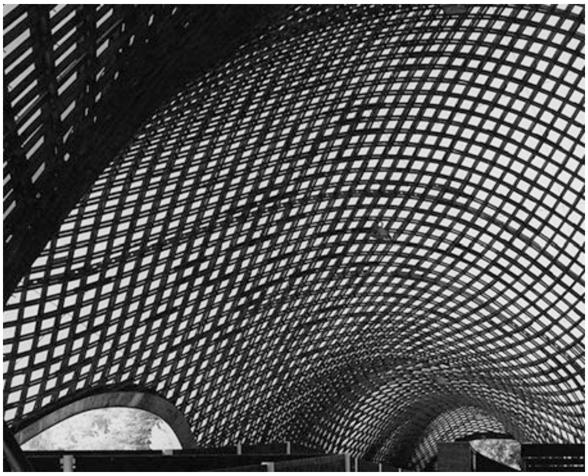
Daylighting Controls, Performance and Global Impacts. Photo 4
Examples from building history: Baroque: indirect daylighting [14]

systems. The ventilation-only systems can be focused on the quality and quantity of fresh air needed in each space, instead of ventilation that is dependent on the variability of cooling demands. Ventilation effectiveness is a measure of the delivery of outside air to the occupant, and many cooling-dominated ventilation systems have compromised ventilation effectiveness. The separation of thermal conditioning and ventilation offers both energy benefits and air quality benefits.

The savings in building and operating costs far exceed the investment costs for new daylight technology and the investments in façades with improved heat protection.

The Challenges of Daylighting

Despite generations of successfully daylit buildings, designing for effective daylighting poses a number of challenges. First, daylighting must be balanced against overheating due to solar gain, a time of day and seasonal design challenge. Second, daylighting is only successful if the brightness contrast of the window or other daylight source is fully managed, and direct glare must also be avoided. Heat loss and heat gain must be managed through the window and skylight areas, since they are typically less resistive to heat transfer than today's wall and roof constructions. Finally, view must be considered a critical component of effective daylight design.



Daylighting Controls, Performance and Global Impacts. Photo 5
Examples of daylighting in modern architecture: Frei Otto: multipurpose hall and restaurant

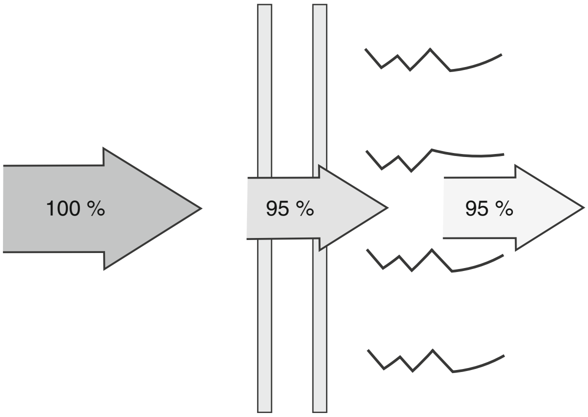
Daylighting Controls, Performance and Global Impacts. Photo 7
Examples of daylighting in modern architecture: Paul Rudolph: Interdenominational Chapel

Daylighting Controls, Performance and Global Impacts. Photo 6
Examples of daylighting in modern architecture: Jørn Utzon: church at Bagsvaerd

Daylighting Controls, Performance and Global Impacts. Photo 8
Color shift through sun protection glass and electrochrome glazing

Daylighting with Effective Shading

Over the past 40 years, the predominant strategy for shading to reduce solar energy transmission into the building is the selection of highly reflective or mirror glass. The low solar heat gain glass reduces the solar



Daylighting Controls, Performance and Global Impacts. Figure 7
Color rendering of low-e glass 95–96%, color rendering of Retro louvers >99% eliminate?

load by reflecting the solar gain at the outer skin with a measurable level of absorption in the glass as well. These low solar heat gain coefficients traditionally ensured low daylighting transmission as well, failing to provide the buildings with sufficient natural daylight. The resulting increase in energy use for electric lighting and associated cooling ensured that the glazed area in buildings had a negative energy balance (Fig. 29).

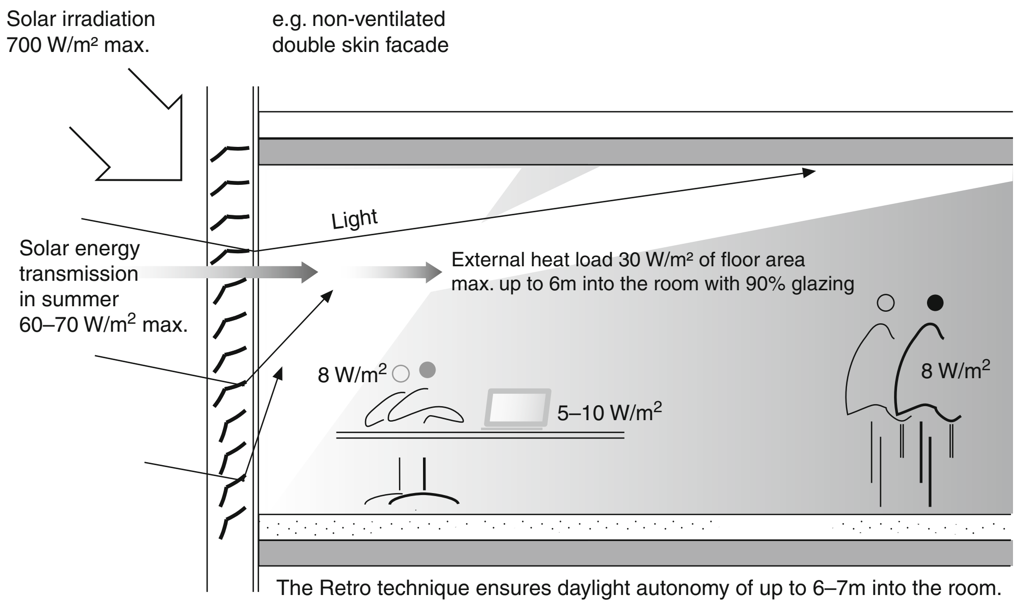
These sun protection strategies, which shade the inside but at the same time darken it to the point of requiring additional electric lighting even while the sun is shining, are, a priori, energetically highly counterproductive (Photo 9). While the use of reflective glass is the most problematic, many external and internal sun protection devices follow the same rule – darken the space to the point where electric light is necessary. This includes, in general, all interior roller shading systems, vertical louvers and colored blinds, and even many external sun shading devices. The loss of daylighting becomes even more profound when internal or external shading layers are used in combination with low transmission glazing.

Shading strategies that do not include specific light redirection or light transmission solutions to improve the natural illumination in the room are a waste of the natural, free resource of daylight and of valuable electricity. Shading measures inside the glazing have further concerns relative to protecting the window zone from overheating, since they convert a percentage of the incident sun into heat through absorption. This is especially pronounced when the internal shades or blinds are dark, generating measurable cooling loads.

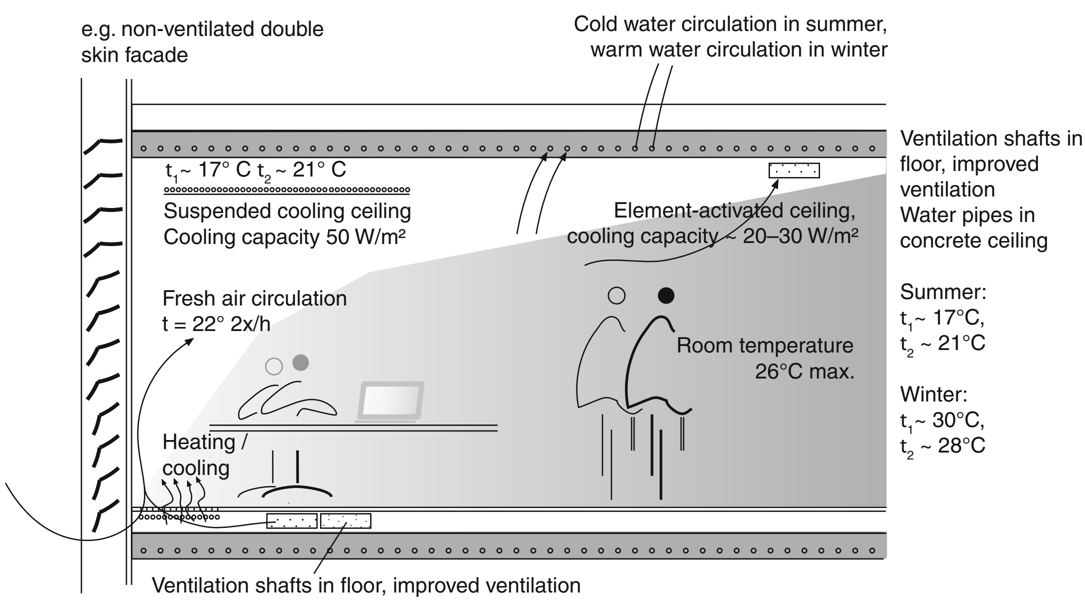
The pervasive loss of daylight as the dominant light source in modern buildings establishes the challenge to develop new strategies in ecological and sustainable building construction. A focus must be given to improving and optimizing the use of daylight without overheating the buildings through solar irradiation.

The first step is the introduction of high visible transmission glass combined with low solar transmission for any building that does not need passive solar heat. In cooling-dominated climates, this can be through high-visible, low-solar glazing materials. However, in mixed or heating dominated climates, the provision of daylight must be accompanied by dynamic shading to ensure the ideal seasonal or even time-of-day energy management. The state of the art for buildings in Europe is low-e glass with a light transmission of 80% and a solar heat gain coefficient or g-value of 55% for year-round daylighting and winter solar heating. This is then combined with dynamic external and internal sun protection for summer SHGC-values as low as 8–15%. Technically, it is possible to lower the SHGC values for the high, overheating sun to less than 5% while still maintaining effective daylighting. These energetic advantages are primarily achieved through light redirection using reflective surfaces within a special, double skin façade (Figs. 5, 19, 31, 32).

It is critical to remember that a building will heat up less in summer as a result of improved daylighting when compared to the use of electric lighting combined with low transmission glazing or glazing assemblies. The sun produces a photometric radiation equivalent of approximately 100–120 lm/W. With low solar/high visible transmission glass assemblies, the lighting energy increases to 200–240 lm/W. On the other hand, the lighting efficacy of fluorescent luminaires is only 60–70 lm/W. Given comparable illuminance solutions (lux [lx = lm/m^2]), buildings are heated three times as much by fluorescent lights as by daylight [2].



a External and internal heat loads in summer



b Heating and AC system concept

Daylighting Controls, Performance and Global Impacts. Figure 8
The Retro technique dramatically reduces the high outer heat loads, making possible new concepts in AC systems. As a result, chilled ceilings are sufficient in most climates to cool a building. (**a**) External and internal heat loads in summer. (**b**) Heating and AC system concept

Daylighting Controls, Performance and Global Impacts. Photo 9
Mirror façades darken the interior, making it necessary to switch on the lights during the day (Photo: Helmut Köster) [21]

Effective Daylight Distribution with Brightness Contrast Control

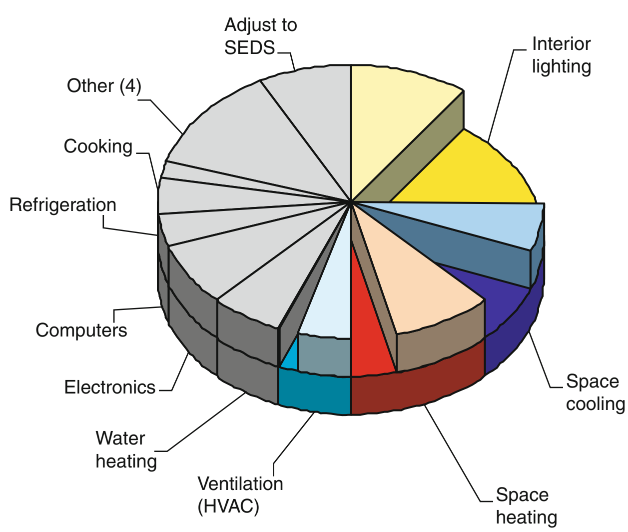
Admitting daylight through high-visible transmission glass is only the first challenge. The distribution of that light to task surfaces, as well as the balance of brightness of various surfaces to ensure managed brightness contrast, may be the greater challenge (Figs. 21, 23, 24, Photos 18, 28).

There are numerous textbooks on the design of window walls in relationship to room proportions and surfaces for effective daylight distribution and brightness contrast control [20]. This entry does not intend to replicate these guidelines, or explain critical diagrams that illustrate the breadth and depth of these design imperatives. It is critical to state, however, that the design solution set will be significantly driven by climate and building function, and will have changing demands based on season and time of day.

Existing daylight design guidelines do not typically resolve the need for greater depth in daylight penetration for today's deeper buildings – to be achieved without glare or overheating. For this reason, it is critical to integrate dynamic controls of the daylight source – the windows and skylights – to ensure effective daylighting and control for solar heat gain. Dynamic controls for light distribution and shading are typically external or internal layers on the glazing,

	Consumption	Consumption
	Standard	Best practice
Interior lighting	25.2%	10.1%
Space cooling	12.5%	5.5%
Space heating	12.2%	8.5%
Ventilation (HVAC)	6.2%	4.7%
Water heating	6.0%	6.0%
Electronics	7.6%	7.6%
Computers	3.9%	3.9%
Refrigeration	4.2%	4.2%
Cooking	1.9%	1.9%
Other (4)	12.6%	12.6%
Adjust to SEDS	7.7%	7.7%

Savings in energy consumption: 27.3 %



Daylighting Controls, Performance and Global Impacts. Figure 9
Energy consumption savings of approximately 27.3% in the climate of Sofia in office buildings by the use of intelligent daylight systems which help to reduce the cooling loads in summer and simultaneously improve the daylight transmission

Daylighting Controls, Performance and Global Impacts. Photo 10
Prisms are translucent but prevent visual transmission [14]

though they can be integral to the glass assembly. In designing the materials and surfaces of these layers, the following light redirection methods are important for consideration: prisms, holograms, mirrors, and hybrid systems.

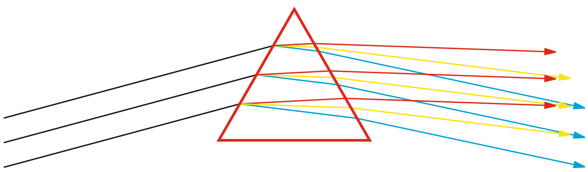
Prisms redirect light through refraction in an optically denser medium, e.g., in acrylic or polycarbonate. Through total internal reflection, it is possible to prevent the light from passing through altogether due to retroreflective properties. The disadvantage of prisms is their lack of transparency. The systems are only transparent to light, offering translucency but not clear views (Photos 10, 11). When daylight passes through prisms and holographs, it is broken up into its spectral colors often creating colored patterns and striations on the walls and ceilings (Fig. 10). On the other hand, the use of laser-cut prismatic panels strategically placed on the inside or outside could ensure excellent views in combination with daylight redistribution (Fig. 11b). This installation, however, does not protect from overheating (Fig. 11c, d) [22].

Holograms are also useful for redirecting light into the depth of the room (Photos 12, 13, 14), but also eliminate transparency for views. They can be combined with electric lighting to offer some dramatic design effects in addition to effective daylight distribution. The foils onto which holograms are imprinted

Daylighting Controls, Performance and Global Impacts. Photo 11
Prisms are translucent but prevent visual transmission [14]

and which are embedded in glass, however, are still expensive, which makes it difficult to use them in larger quantities [13].

Mirror systems provide for a wide range of light redirection effects, depending on their mirror geometry, and they can be used on louvers or blinds inside the glass, within double skin façades (Figs. 31, 32, Photos 16, 17), outside the glass, or even installed in miniaturized form in the gap between the glass layers (Fig. 24, Photos 26, 29, 30).



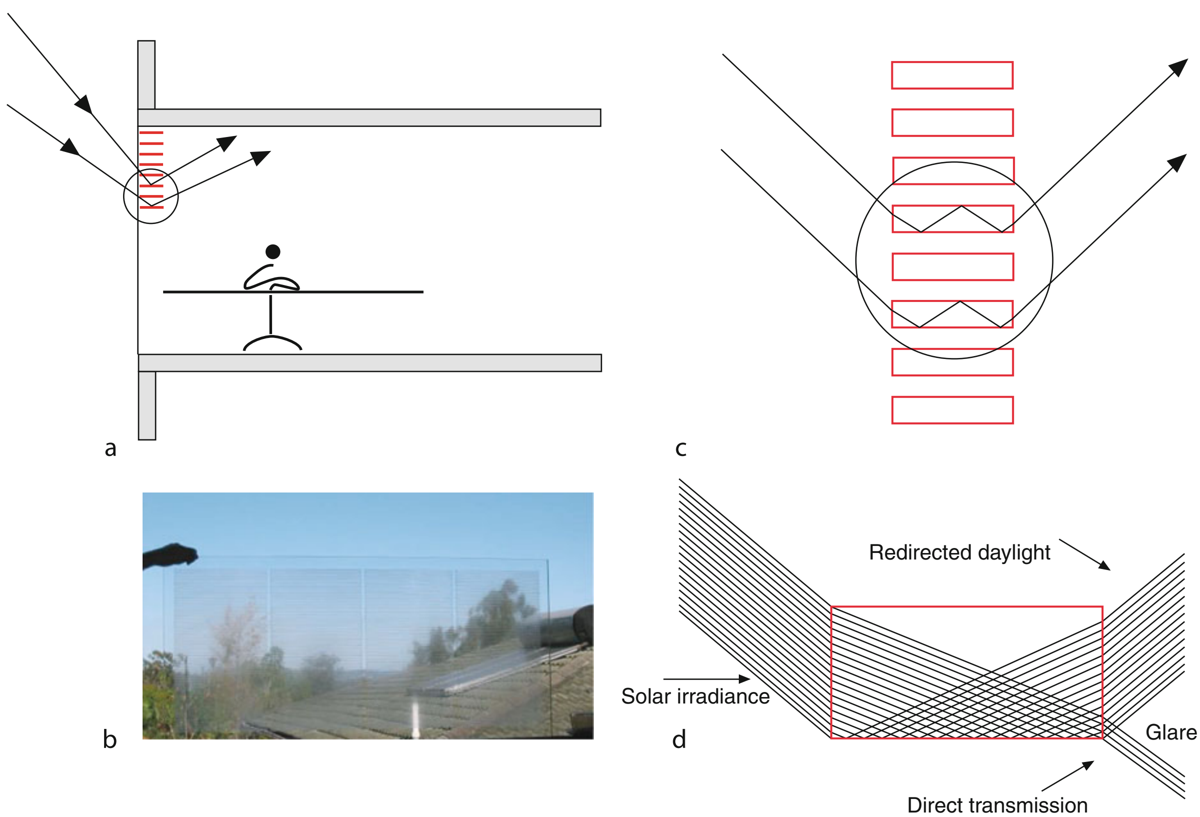
Daylighting Controls, Performance and Global Impacts. Figure 10
Breakup of light into its spectral colors through refraction in the prism

Designing Effective Daylighting

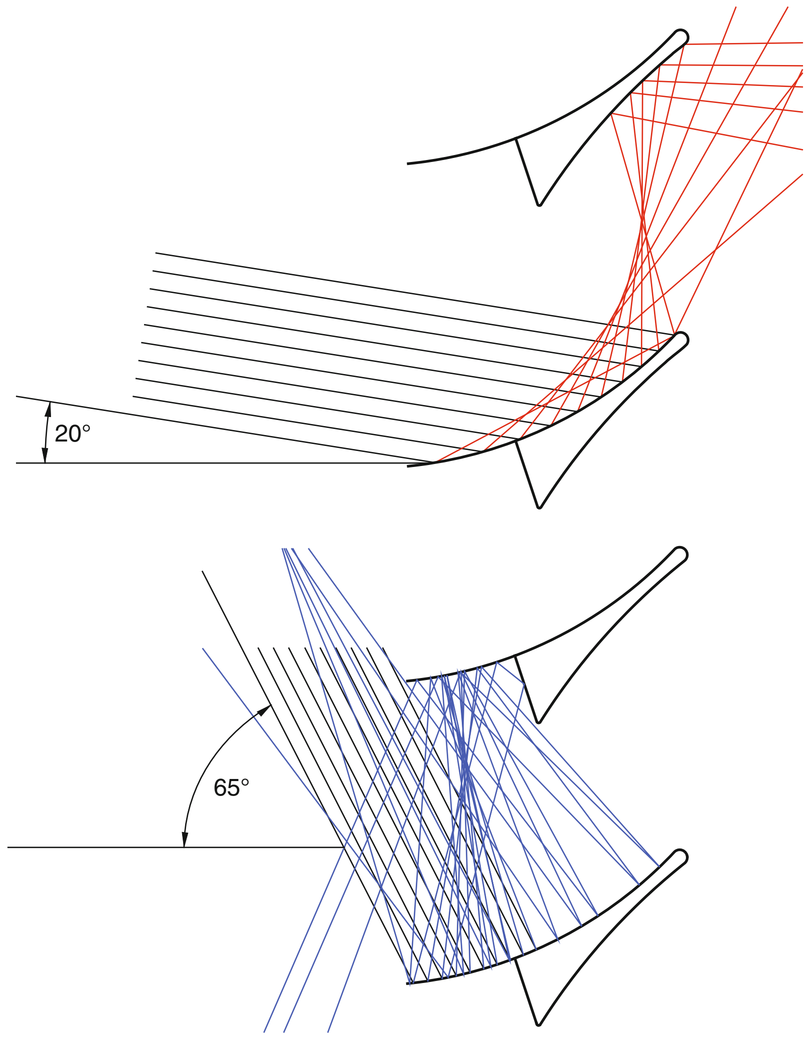
The design of effective window and skylight systems for light and heat management as well as views requires consideration of a number of design variables: façade orientation and louver geometry, louver surface qualities and their relationship to ceiling diffusers, louver controls, and electric lighting interfaces.

Designing Daylighting: Orientation and Basic Louver Geometry

Internal, integral, or external louvers and blinds offer the most strategic solution to meeting the dynamic demands for balancing daylight distribution



Daylighting Controls, Performance and Global Impacts. Figure 11
Light deflection using laser-cut panels, advantage: good visual transmission, disadvantage: risk of overheating

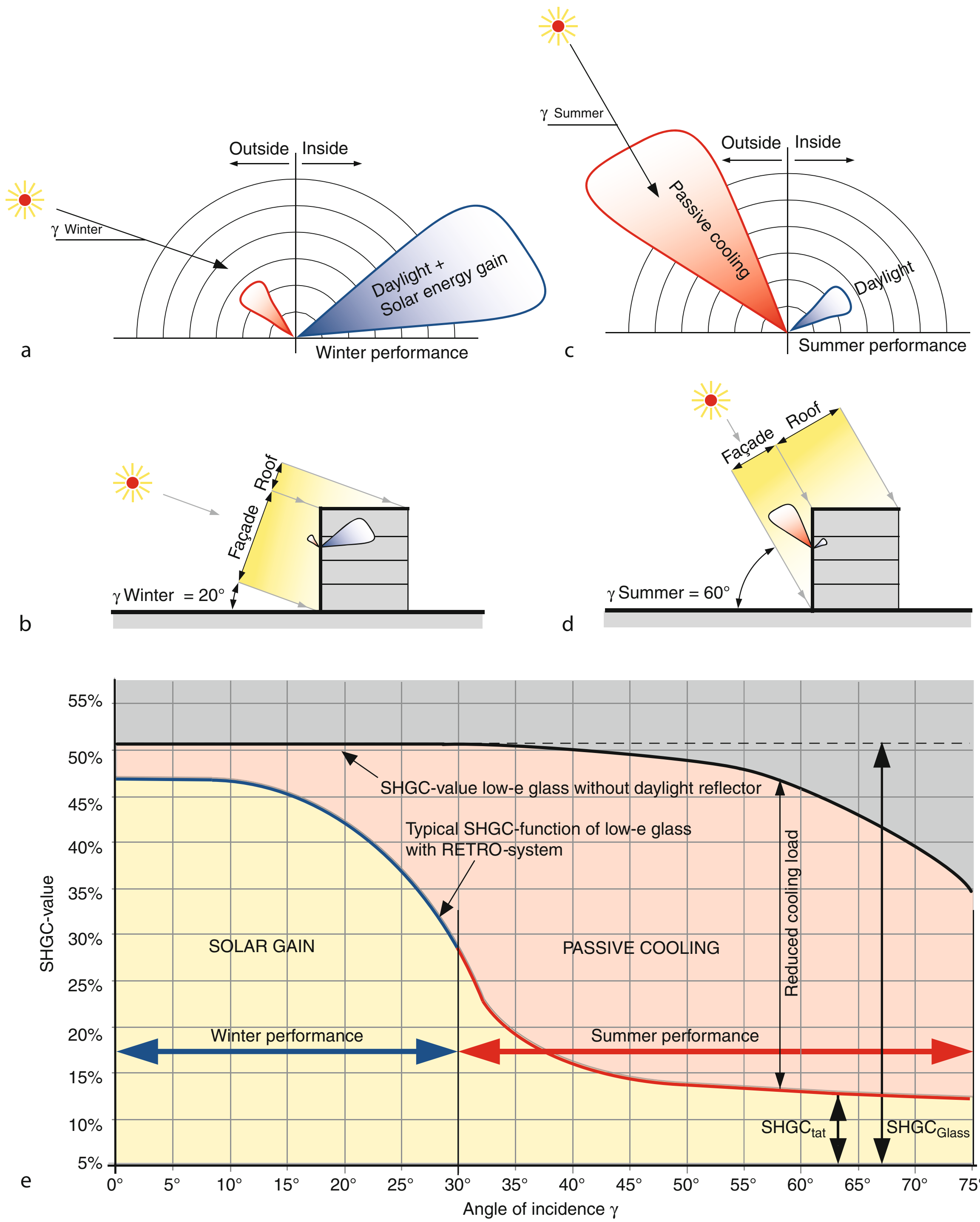


Daylighting Controls, Performance and Global Impacts. Figure 12
Okasolar light reflection louvers in a fixed position inside the glazing with resulting light redirection of the low winter sun and the high summer sun. A next step in the development of the systems involves mono-reflective light deflection which drastically improves the shading capacity of the technology (see also Fig. 16) [EP 0029442; US 4,715,358]

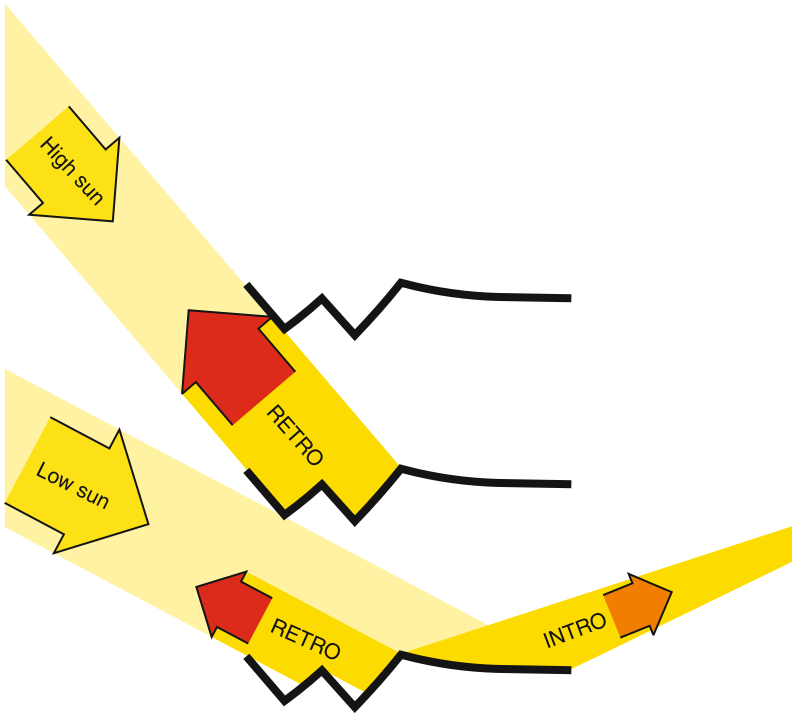
with effective shading. The surfaces of these louvers are critical to daylight distribution, but so is the louver geometry.

Effective daylighting requires varying design responses for different orientations. Japanese design standards for commercial buildings are focused on only providing occupied spaces with south and north orientations to ensure effective daylighting without the overheating or glare that is prevalent on the east and west (Fig. 1). Roofs are subject to much higher energy loads in the summer than east west façades, and significantly more than southern and northern façades. In short, design for effective daylighting without glare and overheating will require unique detailing for each orientation.

The first step to optimizing louver geometry is to recognize that blinds should be inverted from their conventional downward facing arc to an upward facing



Daylighting Controls, Performance and Global Impacts. Figure 13
(**a–d**) Thermal loads for roofs and façades. (**e**) Given the distinctive heating and cooling periods in the European climate, intelligent daylight technologies can maximize solar energy gain in winter and achieve effective shading for natural cooling in summer. These two conflicting goals are achieved through utilization of the sun's changing angle of incidence even without tilting of the blinds



Daylighting Controls, Performance and Global Impacts. Figure 14
Light redirected on a RetroLux louver (see also Fig. 23). The overheating summer sun is retroreflected on the horizontal, open louvers. Daylight from diffuse sky and a low sun is supplied via the light shelf. [US 6,240,999; US 6,845,805; EP 0793761; EP 1212508]

arc intended to move daylight further into the space, working in combination with the ceiling as a reflector (discussed in a later section).

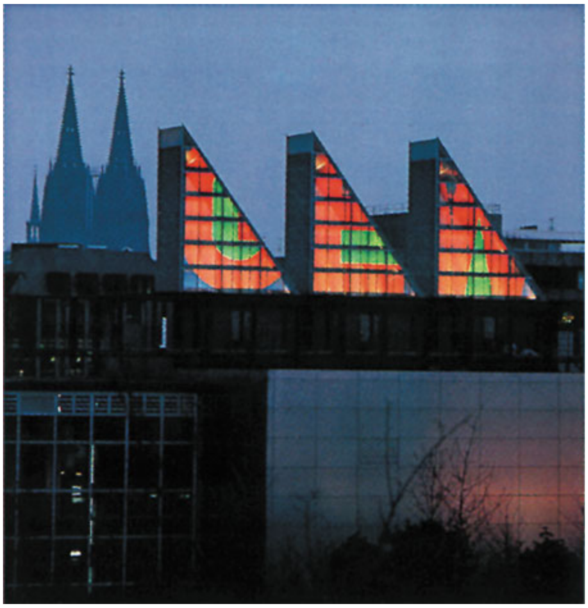
The second step to optimizing louver geometry is to include the elevation angles of the sun in the design of even fixed systems, appropriately controlling thermal energy and light transmission by season. The sun in winter shines at a lower angle and in summer the angle is significantly higher. Consequently, it is necessary to design a louver geometry which redirects the low winter sun to a greater degree into the building, while reflecting the high summer sun to a greater degree back outside. This is in order to achieve a homeostatic balance of the building in accordance with the heating and cooling periods in different seasons (Fig. 15).

The development of light redirection systems is dependent on defining the friend/foe relationship with the sun in different climates and cultures: How much of the solar irradiation should be reflected back to the sky for passive cooling comfort? How much should be directed inside for daylighting of the interior? How much can the amount directed inside increase if passive solar heating is desired (Table 1, Fig. 13)

Such complex, contradictory demands for controlling energy transmission require precise mirror geometries. Horizontal louvers are most useful for refining energy transmission because they can respond to the solar altitude angle even without adjusting the louver position, and because they are best suited to ensure illumination into the depth of the room in combination with the unobstructed ceiling plane (Fig. 24). Vertical louvers or blinds, on the other hand, only respond to the azimuth of the sun without redirecting light toward the ceiling. They are merely suited to provide shade. The benefit of even fixed light redirection louvers with geometries optimized for summer shading is tremendous, as shown in Figs. 13 and 14.

Daylighting Controls, Performance and Global Impacts. Photo 12
Holograms for light deflection produce excellent design effects using artificial lighting [14]

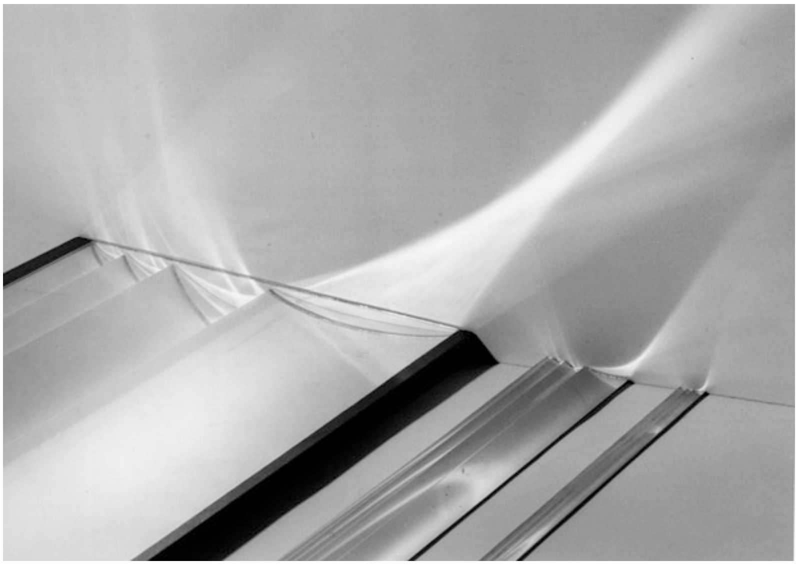
Daylighting Controls, Performance and Global Impacts. Photo 13
Holograms for light deflection produce excellent design effects using artificial lighting [14]



Daylighting Controls, Performance and Global Impacts. Photo 14
Holograms for light deflection produce excellent design effects using artificial lighting [14]

Designing Daylighting: Louver Surface Qualities

Blinds should be designed both as shading devices and as light shelves. Maximizing the use of daylight with well-managed and comfortable illuminance levels, while minimizing solar overheating, can best be achieved through the louver contour and their optical characteristics. While mirrored surfaces are very effective for reflecting daylight deeper into the space, the surfaces of blinds can be significantly more refined to differentiate between high sun angle summer sun and low sun angle winter sun. Precise, mono-reflective surfaces can redirect daylight toward the ceiling and into the depth of the room.



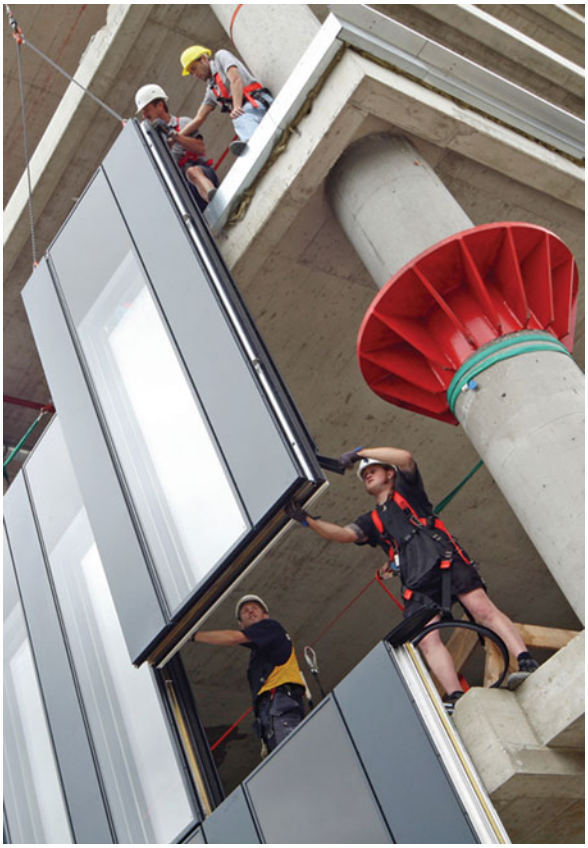
Daylighting Controls, Performance and Global Impacts. Photo 15
Light deflection using RetroLux™ louvers (see Fig. 7). Optical systems can be reduced or increased in size. The picture shows a 50-mm-wide louver, a 200-mm louver, and a large 2,500-mm louver. It illustrates how the high summer sun is reflected back outside while daylight is redirected to improve the illumination inside

Daylighting Controls, Performance and Global Impacts. Photo 16
Head office of Energie AG, Linz, Austria, Architects: Weber Hofer Partner, Zurich

Precise guidance of the daylight using optimized mirror geometries can also prevent the bottom sides of the louvers from exposure to sunlight, which would produce glare and turn the blind into an unwanted surface emitter or even a heat radiator. Only mono-reflective structures ensure that incident sunlight is redirected either into the depth of the room and/or back outside, without a ping-pong effect between the louvers themselves (e.g., Fig. 12). Mono-reflective systems are easier to optimize in terms of their energetic and lighting capacity, and their thermal performance can be precisely calculated even in the building simulation phase (Figs. 18, 20, 23, 24). In addition, the underside of the blinds should not be mirrored, to avoid reflective glare.

Designing Daylighting: Innovative Louver Geometries and Surfaces

There are dozens of macro- and micro-design choices that can make a horizontal blind into an even more



Daylighting Controls, Performance and Global Impacts. Photo 17
Head office of Energie AG, Linz, Austria, Architects: Weber Hofer Partner, Zurich

effective light fixture – with both glare and heat control. Surface reflectivity/absorptivity and finish, geometries of the outer and inner surfaces, W- and V-shaped blinds in addition to curved blinds with micro-features such as Fresnel surfaces, and innovative assemblies will be discussed further (Fig. 15).

If conventional blinds are inverted and mirrored on their concave upper side, they will indeed redistribute daylight to the ceiling and as a result to deeper portions of the room. However, the lower blinds will first direct light to the occupant, creating glare that makes it necessary to close at least the lower section of the blind (Fig. 16). As a result, visual contact with the outside is lost, and if the upper portion of the blind cannot be controlled independently, effective daylight will be lost. Even in the upper section of the window, open louvers can create glare in open plan offices whenever the sun angle is low, streaming between the blinds into the space.

In addition, studies of daylight redirection blinds revealed a second area of concern. With higher sun angles in the summer, or a greater steepness for the blind, some of the daylight that is reflected off the blind will fall onto the bottom side of the louver above. The underside of the louvers will absorb a portion of this reflected light and heat up the window zone, even in summer (Fig. 17).

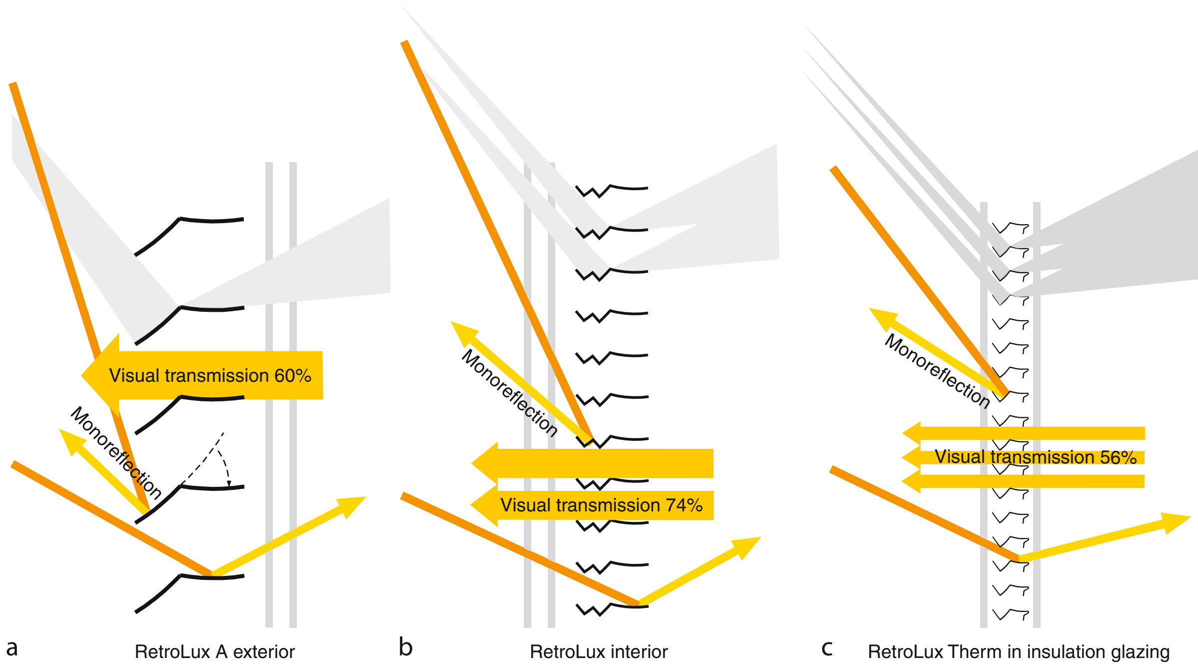
These studies led to the development of more optimized light redirecting louvers that combine surfaces and geometry to manage light in different seasons. One strategy would be to pursue micro-structural or prism innovations, embossing fresnel mirrors onto a concave louver (RetroFlex type louver systems) (Figs. 18a, c, 19, 31, 36). With a crafted fresnel surface, an open, horizontal louver will reflect the sun back to the outside to prevent overheating while allowing for 80% views and diffuse daylighting.

Above the seated window, the mirror prisms can be placed on the underside of the concave blind so that light falling onto their reflecting upper side is redirected to a greater degree into the depth of the room (Figs. 18d, f, 37).

The combination of sunlight-reflective louvers in the viewing area and underside micro-structured louvers above 1.8 m creates a blind assembly that protects the occupants near the window from overheating and glare, while ensuring more effective daylighting, entirely without the loss of views. Since all louvers are positioned identically depending on the sun's angle of incidence, they are easy to operate.

These micro-structured louvers are less than 0.4 mm thick, have a width between 25 and 80 mm depending on density desired, and be positioned inside or in-between a double skin façade (Photos 16, 17, Fig. 31).

While micro-structured louvers offer significant gains over conventional blinds, the best approaches to minimizing heat gain in summer while maximizing daylight requires more challenging geometric solutions. A critical first step is to divide each louver into

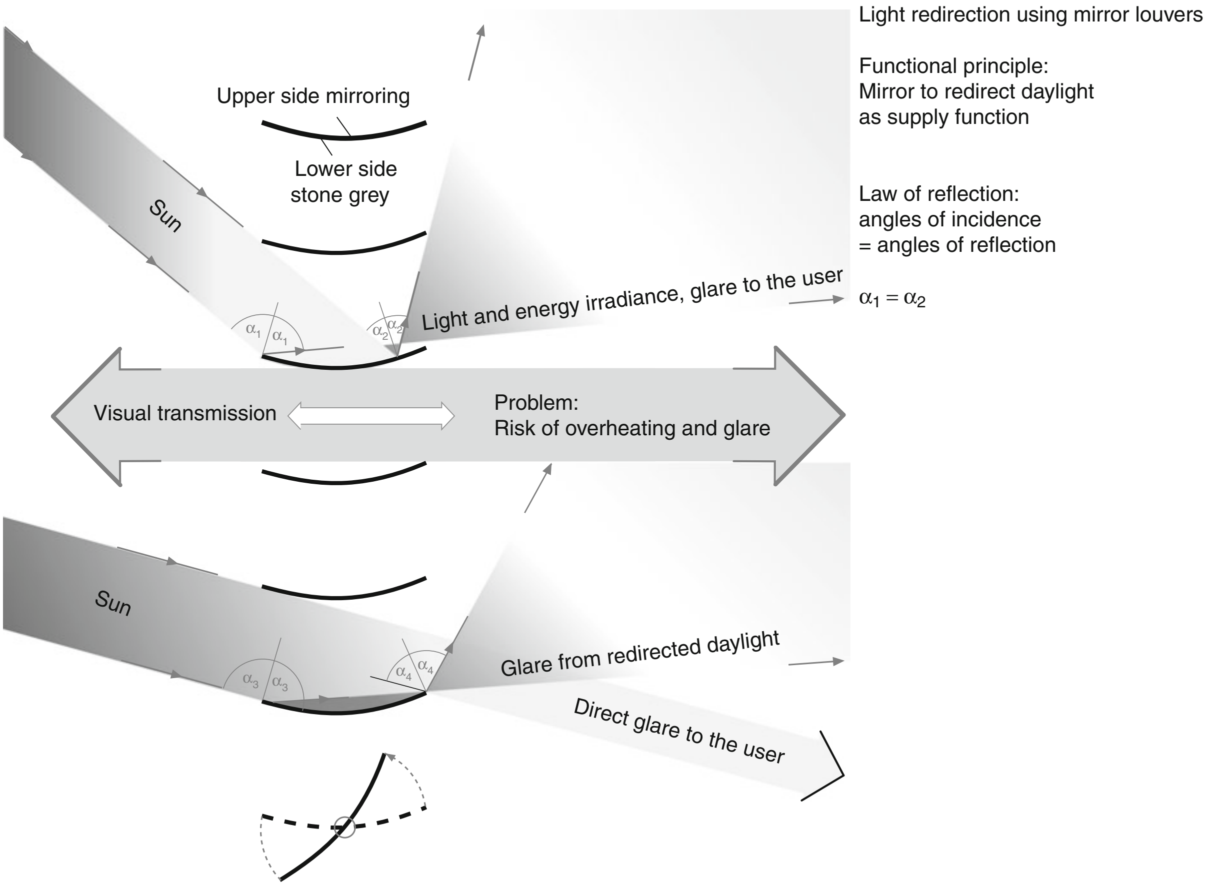


Daylighting Controls, Performance and Global Impacts. Figure 15
RetroLux systems ensure simultaneity of retroreflecting the overheating summer sun on the retroreflector, redirecting diffuse daylight on the light shelf and good visual transmission

two sections – redefining external and internal edges with different optical characteristics to respond to the different seasonal positions of the sun in the sky. Given the distance of the louvers from each other, the summer sun only falls onto the section of the louver oriented toward the outside. The outer half of the louver can then reflect the high, direct sun back out for natural cooling, while the inner half of the blind can direct the low-angled sun inside to improve illumination of the interior and support passive heating (Fig. 20).

Daylight-optimized louver geometries thus ensure solar heat control based on the sun's angle of incidence without the need for continuous readjustment of the louvers in line with the incident sunlight. On the outer section of the louver, the high summer sun is monoreflectively redirected back into the sky (protective function) and on the inner section of the louver, low incident sun in winter is directed inside (supply function) (Figs. 15, 20, 22, 23). The blinds only need to be closed when the sun is very low and grazing light between the louvers causes glare. The geometries of these blinds and their degree of separation are established based on climate, latitude, and orientation, but there are some truisms for the designer. The further the building is from the equator, the lower the sun is and the longer the heating season is. The angle of incidence increases the closer you get to the equator, along with the temperatures.

The height of the work plane and the eye position of both seated and standing building occupants is an important consideration in daylight design for both glare control and quality views. While the use of reflected light off of the ceiling plane provides good uniformity over a greater depth of the space, any blinds below typical sill height of 1 m or less may create glare by reflecting light directly into the eyes of the occupants. To optimize the illumination

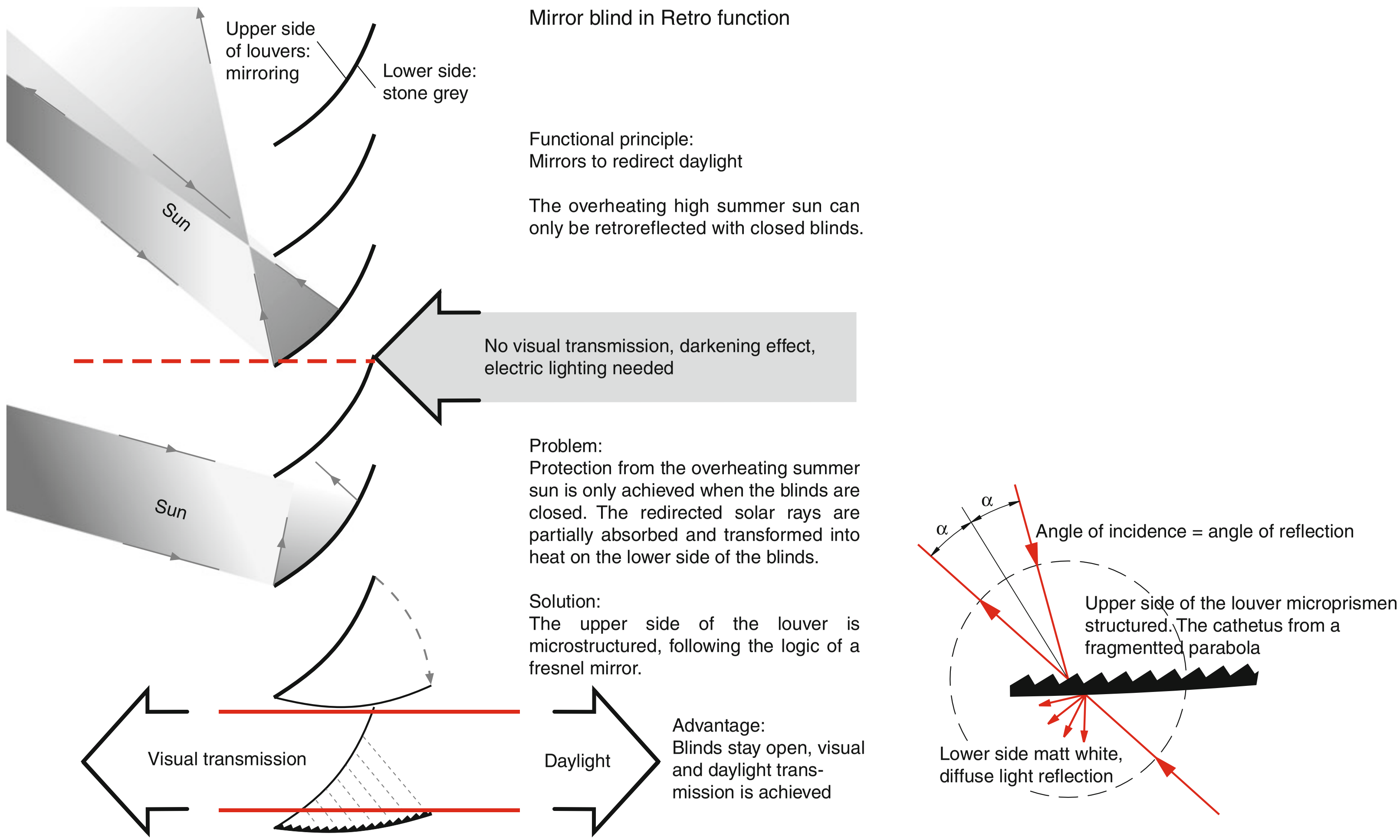


Daylighting Controls, Performance and Global Impacts. Figure 16
Mirror blinds open

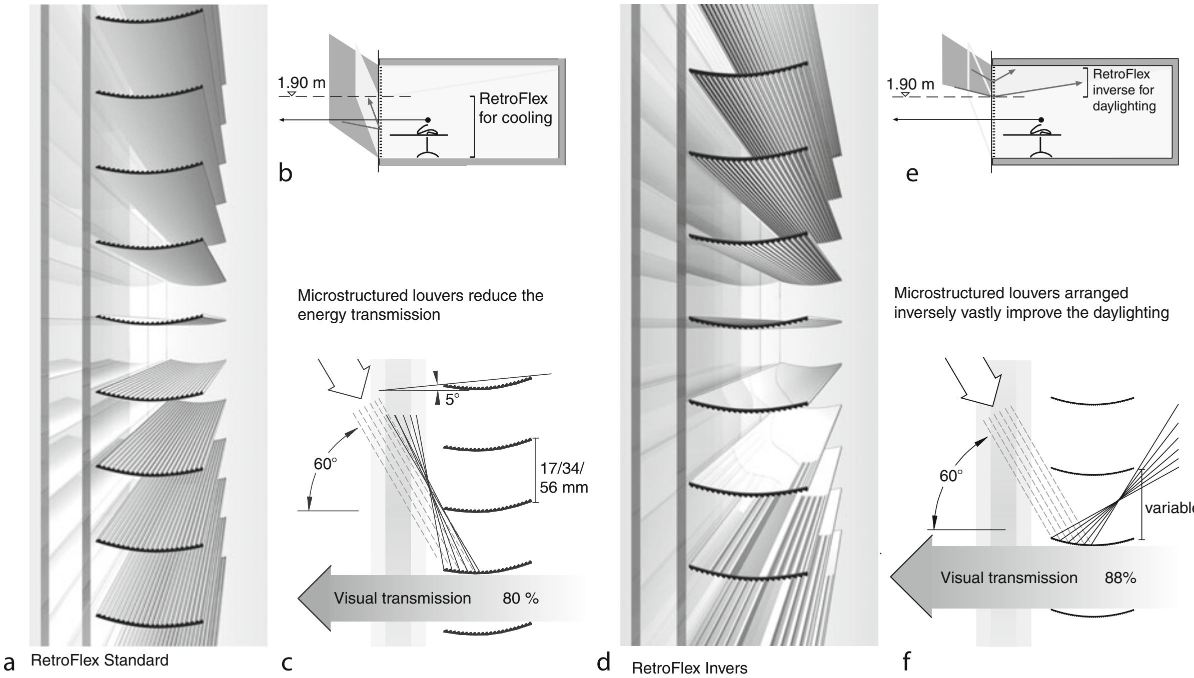
into the depth of the room, it is necessary to split the façade into upper (clerestory), middle (viewing), and lower (below the sill) zones. In the upper, clerestory section of the window, daylight should be redirected at a shallow angle to maximize daylight distribution deep into the room. In the middle, viewing section of the window, a somewhat sharper angle is required to redirect the light toward the ceiling to eliminate direct glare, while still maintaining as clear a view as possible. In the lowest section of the window, below the normal sill line, the sharpest reflection angle is important (Figs. 21, 22, 15, 23) (Photo 18).

In addition to the V-shaped geometries described, a W geometry can also support effective daylighting and views with reduced glare and overheating. The W-shaped louver for interior use can offer a slimmer profile in manufacturing and support 76% visual transmission in an open position while the high summer sun is simultaneously reflected outside (Fig. 14).

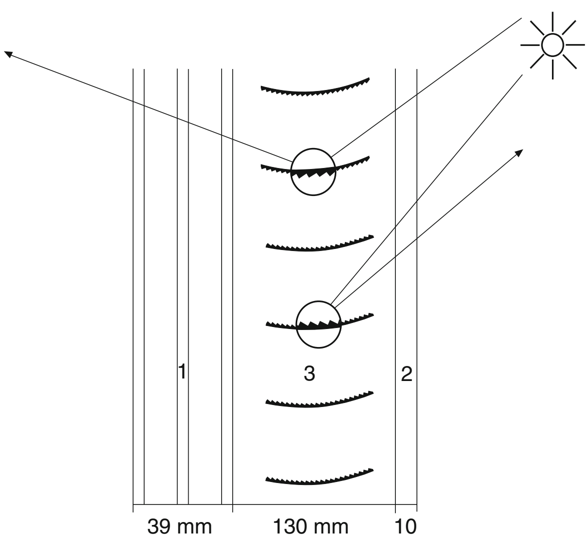
The term “retro” refers to the deflection of light, i.e., the protective function of systems through which the sun is reflected back into the sky. The result, however, can be unwanted glare in the interior due to reflections from the glass. The skill in developing “retroreflective” systems is to guide the light in such



Daylighting Controls, Performance and Global Impacts. Figure 17
Genesis of a daylight reflecting louver [US 6,367,937; US 6,845,805; EP 1212508]



Daylighting Controls, Performance and Global Impacts. Figure 18
Louvers with microstructured upper surfaces to reflect solar heat gain back outside while supporting diffuse daylighting and views and micro-structured undersides to redirect daylighting into the depth of the room [US 6,367,937; US 6,845,805; EP 1212508]

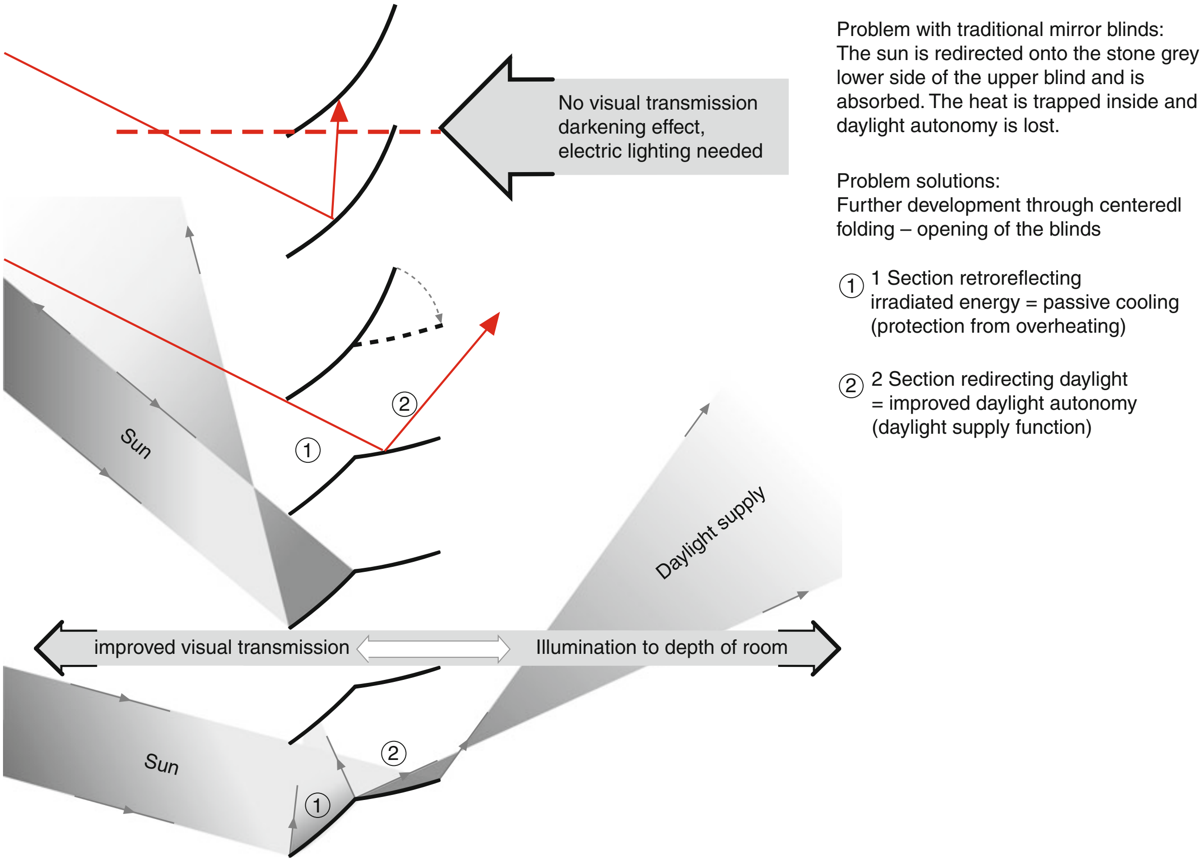


Daylighting Controls, Performance and Global Impacts. Figure 19
Non-ventilated double skin element façade with RetroFlex. U-value of façade 0.65 W/m^{2}K, SHGC value of glazing 0.05–0.1 with open louvers, depending on angle of incidence

a way that the sun rays do not glare in the glass (Photo 27a/b) and thus not visible from the seated position. The light redirection system must be designed such that the sun reflected in the glass hits the bottom side of an upper louver instead of reflecting inside. Louvers following this design rule ensure glare-free transparency of the glass. At a high solar elevation, the visual transmission of such blinds is between 70% and 80% [3].

Macrostructured louvers can also be designed as an integral component of insulated glazing. At 20 mm in width (Fig. 24; Photos 20, 21, 22), the louver section is designed in the shape of a V to stabilize the louver and keep it from bending (Photo 15).

Light-redirecting louvers can also be installed in glazed roofs and set at different angles. Here, the louvers should preferably be installed in a fixed, pre-calculated position in between the insulation glass. Versions which can be tilted and tracked like blinds are, however, also possible (Photo 23).



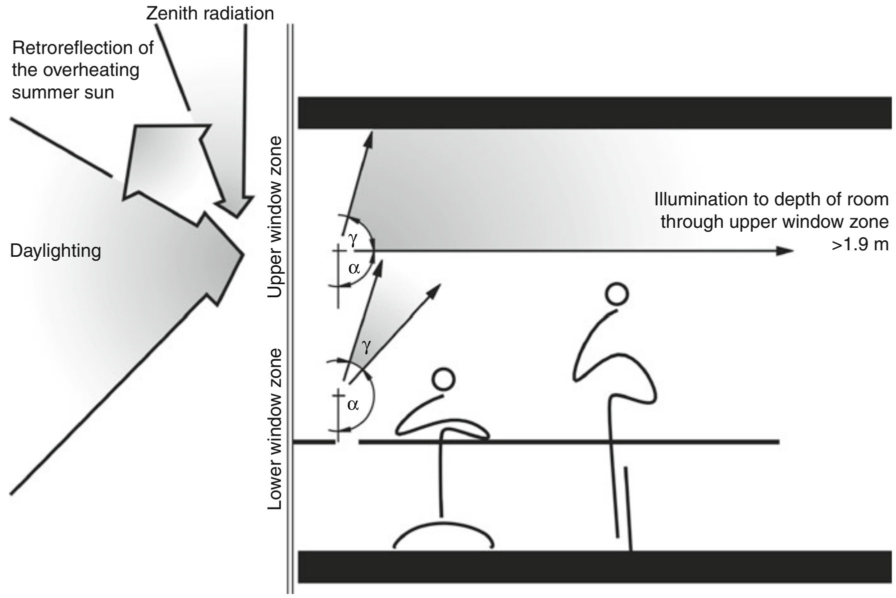
Daylighting Controls, Performance and Global Impacts. Figure 20
Folded mirror louvers as exterior blinds with integrated protection and supply functions through formation of two functional mirrors, a retroreflector toward the outside and a light shelf toward the inside [DE 10260711]

Designing Daylighting: Controls – Balancing Light, Shade, and View

Managing glare, views, and shading as well as electric lighting and air-conditioning energy savings is strongly dependent on louver adjustability and control. On the one hand, controls should respond to weather changes, while on the other hand, changes should be kept to a minimum to avoid annoying users.

While energy optimization might recommend continuous blind adjustment, building occupants might prefer no adjustments, suggesting that louver controls be kept to a minimum of one to three positions throughout the day. East and west façades certainly will need the louvers to be adjusted when the sun rises and sets, and personal preferences will also suggest that some level of control be provided.

Cloudy skies specifically can cause significant glare due to sky brightness. Lights are often switched on during the daytime to avoid contrast glare between the bright sky and the unlit window frames or to compensate for lower illuminance further in the room. Sunny skies can result in direct glare whenever sun angles are low enough to enter directly, and blinds are often closed as a result. Some diffusing shades, designed to reduce direct glare and brightness contrast while allowing views,



Daylighting Controls, Performance and Global Impacts. Figure 21
Angles of light redirection façade

actually make the glare even worse, which also results in the turning on of electric lights. The key to effective daylighting is the ability to dim and redirect light and thermal energy from solar irradiation – independently.

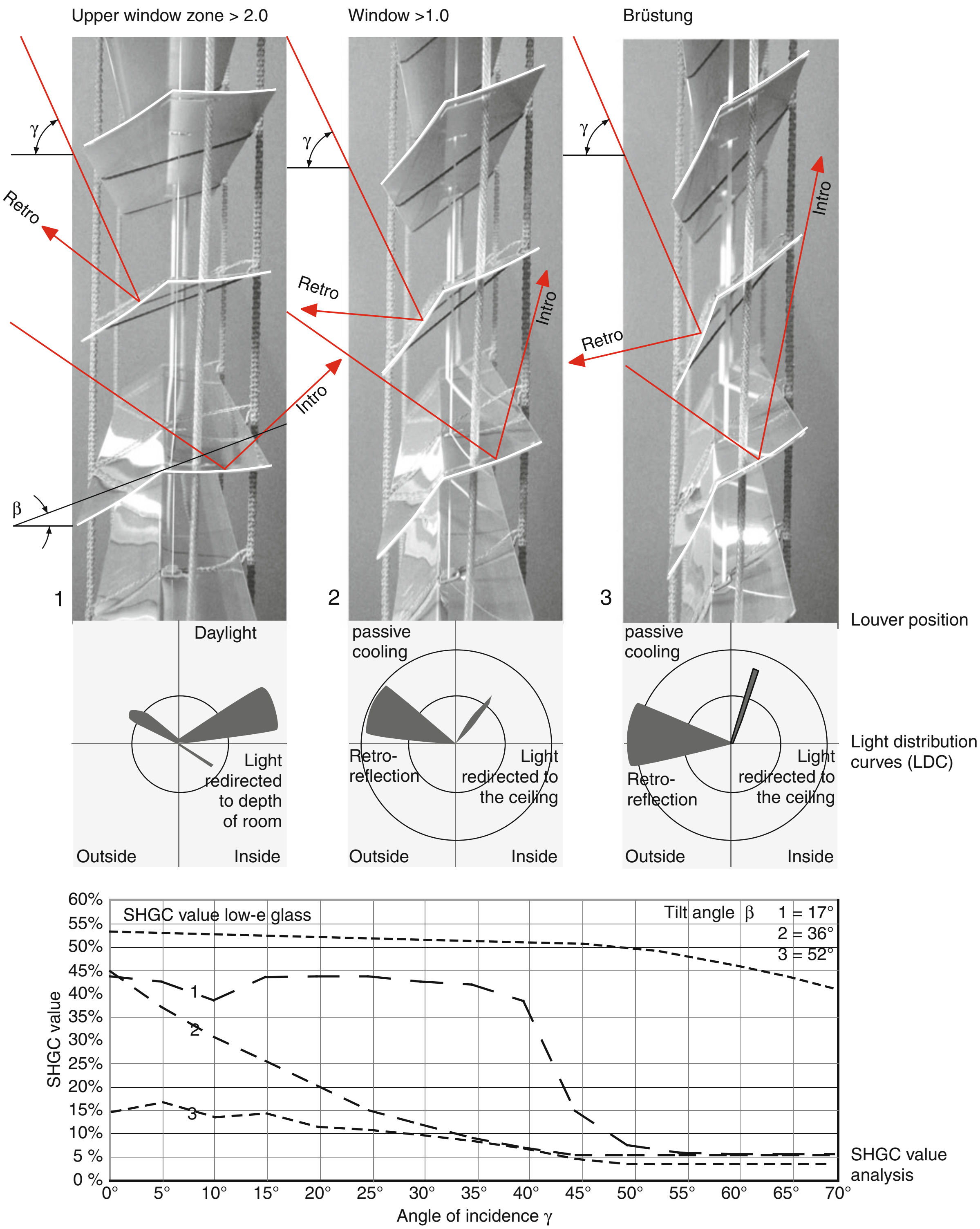
Blinds can be controlled manually with simple guidelines, or controllers can be programmed to respond to calendar or light sensor information to adjust blinds for the optimum balance of view, daylight, and solar heat. Well-detailed blinds can ensure quality views, effective daylighting, at the same time as effective shading, with controls simply extending the long-term performance. Even with the blinds in a permanent down but open position, views can be excellent, while the carefully designed blind geometries and surfaces ensure seasonally differentiated daylight redistribution to the inside and solar heat reflection back to the outside (see Photos 24, 25).

Additional energy savings can then be provided through controls. During the summer, adjusting the light redirection louvers into a closed position when the sun is low on the east or west facing sides of the building can significantly reduce solar energy transmission. Closing the blinds at the end of each work day and opening them again in the morning before work begins can provide additional shade in the summer, or protection against heat loss in winter, during times when daylight and view are not needed (Fig. 25). It is, however, important to open the blinds during the day in order to gain sufficient daylight and views and save electric lighting energy.

In conclusion, the time of day and seasonal dimming and redirection of daylight can best be achieved by careful design of horizontal blinds – their geometries, surface qualities, and levels of adjustability (Photo 26, Fig. 17).

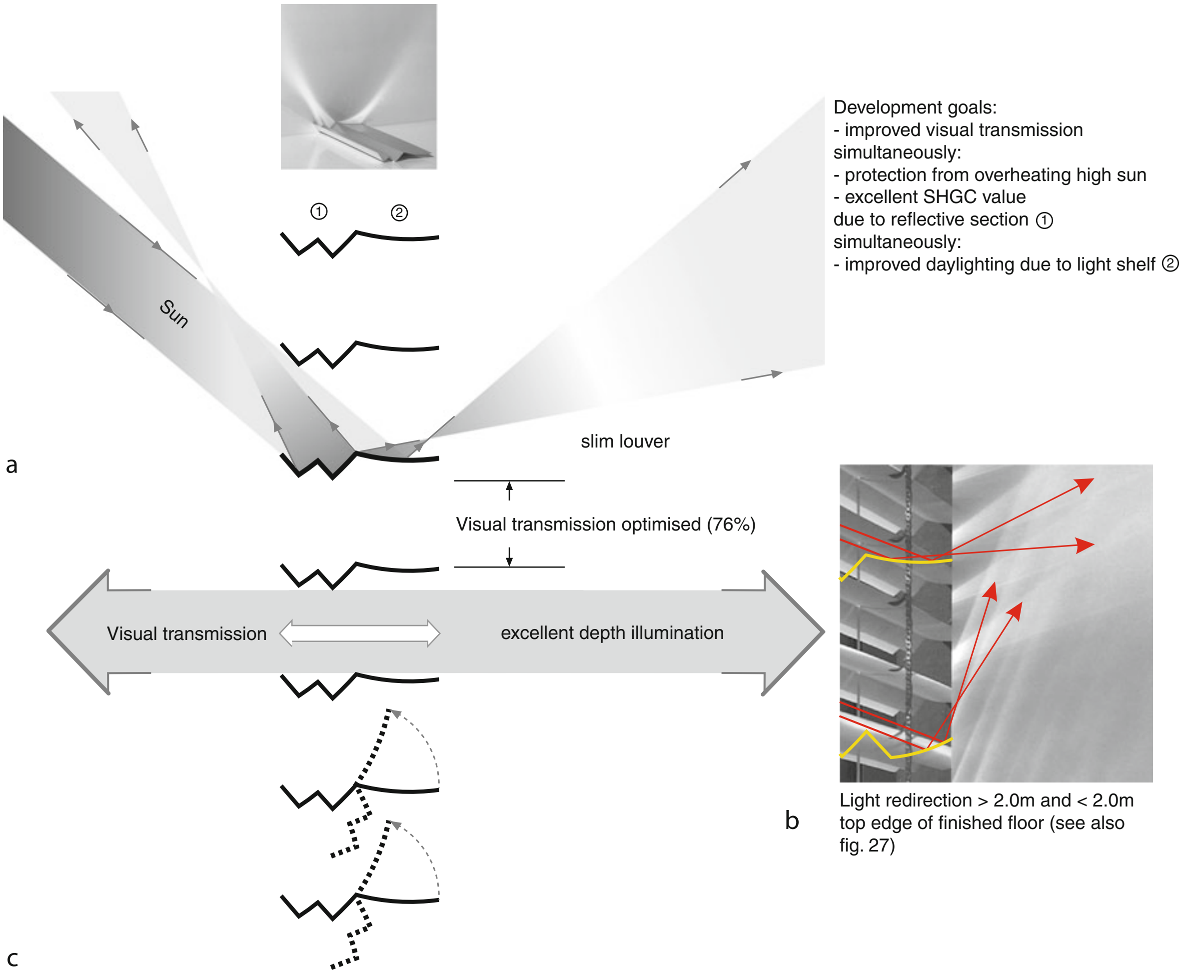
Designing Daylighting: Light Redirection Ceilings

The ceiling is an integral component in effective daylight distribution. Well-designed electric fixtures capitalize on the quality of the reflector as well as the effectiveness of the lamp and lens. Large windows



Daylighting Controls, Performance and Global Impacts. Figure 22

Three Louver positions in floor-to-ceiling blinds for optimum optical performance; analysis of the SHGC values of blind sections 1–3 are an average for all angles of incidence [DE 10260711]



Daylighting Controls, Performance and Global Impacts. Figure 23
Functions of the macrostructured louver "RetroLux" in the upper and lower parts of the blind for glare-free redirection of daylight into the depth of the room and toward the ceiling [US 6,240,999; US 6,845,805; EP 0793761; EP 1212508]

without light redirection systems result in an uneven illumination of the room with excessively high illuminances in the window zone and considerable brightness contrasts (Photos 27a, b). Daylight redirection louvers shift the focal point of daylight design to the ceiling (Fig. 26).

Daylight reflected from the window to the ceiling allows light to be redirected onto the work surface with similar effects as those of conventional electric lighting, but without shadowing (Photos 29, 30).

Reflecting ceilings bear the risk of glare, particularly when viewed from deeper in the room. Consequently, light redirection ceilings and their reflective characteristics and geometry need to be carefully planned. At a very minimum, the ceilings must have the maximum possible light reflection properties, with a modest level of diffusion to reduce glare.

At an optimum, the design requirements for a light direction ceiling equal those of parabolic surfaces

Daylighting Controls, Performance and Global Impacts. Photo 18
Lighting requirements of a daylight façade for glare-free workplaces

Daylighting Controls, Performance and Global Impacts. Photo 19
Daylight façade with RetroLux (Fig. 15), municipal works, Bochum, Germany. Architects: Gattermann + Schossig, Cologne

within luminaires. The light redirection and the cut-off angles of the ceiling must be precisely defined and are subject to the requirements of DIN EN 12 464. Superior redirection characteristics can be achieved by using micro-prism structures which redirect the light from the window downward in precise angles due to their angled prism edges. Prism-structured, convex-shaped louvers can be arranged parallel to the façade in order to ensure sufficient dispersion while reacting to different angles of incidence of the daylight.

Daylight reflective ceilings serve the purpose not only of redirecting daylight, but also of redirecting complementary electric lighting that may be installed at the façade, as described in the next section (Fig. 27).

Integration of Daylight and Electric Lighting

European workplace regulations [1] often stipulate individual access to daylight and visual connection with the outside, such that permanent workplaces are frequently found within 6–7 m of windows. However, deep open-plan landscapes are common in many other countries, with boxed-in workplaces separated by seated or standing height partitions

Daylighting Controls, Performance and Global Impacts. Photo 20
RetroLux Therm in insulation glass (Fig. 24)

that eliminate effective daylight and visual access to the outdoors, and consequently necessitate daytime use of electric lighting.

In Europe, workplaces which do not provide a seated visual connection with the outside are considered inferior. In the USA, no laws exist to ensure seated views of daylight for workers, resulting in the extensive use of electric light during the daytime. In emerging hot countries as well, offices are being moved away from the window to reduce sunlight exposure. While on the surface, rooms without daylight exposure are easier to cool, the electricity used for lighting often exceeds that used for cooling. It is here, in particular, that daylight façades capable of managing solar factors and heat loads, climate by climate, will have the greatest benefits.

First façades and interior layouts must be designed for effective daylighting, as previously discussed. Then, electric lighting must be designed to complement the daylight, filling in when and where daylight is inadequate.

Traditionally, lighting design considers buildings exclusively at night. To date, the dogma of uniform interior illumination has largely been the priority and a feature of good lighting design. The demands for uniformity may be one reason why daylighting has been so quickly abandoned, in addition to the unmanaged solar heat gain that often accompanies daylight. Workplaces in the window zone will always be brighter than those further inside. The uniformity of illumination can be improved by redirecting the light from the window via the white, reflective ceiling into the depth of the room. Diminishing daylight should then be complemented by increasing levels of electric light, shifting the lighting design goals from total uniformity to ensuring task lighting levels and managing brightness contrast throughout the workspace.

Electric lighting can then be controlled based on the illumination levels needed at various workstations in the room. This is effected either through dimming of individual lamps as needed, or through cascade switching, where the lights furthest from the window are turned on first, cascading on row by row as daylight diminishes. Daylight-responsive controls for electric lighting are minimum requirements in energy-optimized building.

However, lights should remain switched off during the daytime, at least within the first 6 m of the window, to maximize use of the natural, free resource of daylight. Recently, a new generation of "integral" controls have become available which switch on the electric lighting whenever blinds are closed. These types of control are the result of observations that conventional interior or exterior blinds darken buildings even when the sun is shining outside! The promise of daylight technology cannot be fulfilled with such cross-purposes.

As a minimum requirement, daylight autonomy should be at least 80% for the first 6 m into the room (Fig. 29). In hot climates, effective daylight should be provided without exceeding a maximum total solar energy transmission (heat load) of 10–12%.

Daylighting Controls, Performance and Global Impacts. Photo 21
The glazed facade is retro-reflecting the overheating sun but supplies the room with more daylight via the ceiling. The workplace is glare-free illuminated. In the openable window area the blinds are moved up to show the effect of the sun without redirecting louvers

Daylighting Controls, Performance and Global Impacts. Photo 22
Examples of illuminating a room using RetroLuxTherm in insulation glass as shown in Fig. 24 (Photo: Helmut Köster) [21]. The redirecting louvers are integrated as fixed systems within the insulation glass of the large glazing. Interior, behind the openable windows venetian blinds with redirecting RetroLux louvers are mounted

Daylighting Controls, Performance and Global Impacts. Photo 23
Light deflection in roof glazing either in insulation glazing or below the glass roof, e.g., with RetroFlex louvers

Daylighting Controls, Performance and Global Impacts. Photo 24
RetroLux in solar protection position and closed position

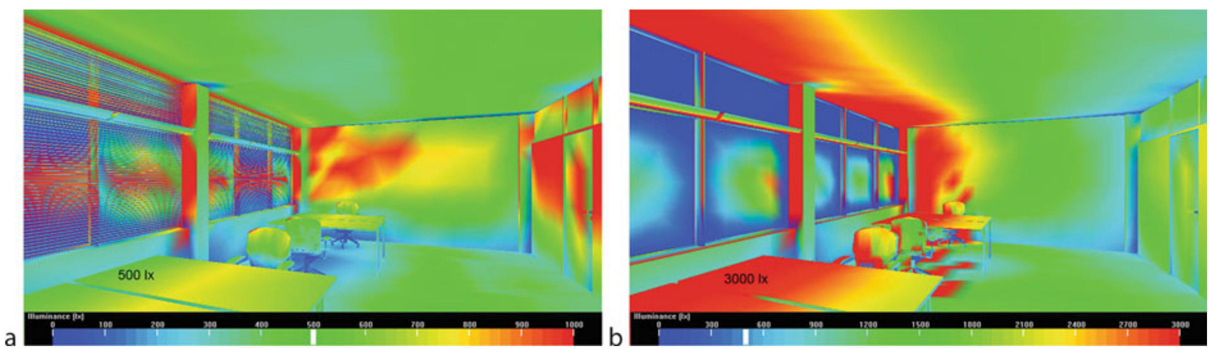
Daylighting Controls, Performance and Global Impacts. Photo 25
RetroLux in solar protection position and closed position

Indeed, good visual transmission (views) and optimized daylight conditions in the interior can be achieved at even 5% total solar heat energy transmission through the façade. In cold climates, heat gain with light gain will be paired goals, and geometrically optimized and controllable blind design can effectively manage climates that have both heating and cooling loads.

The aim of intelligent combined daylight–electric light controls must be:

– To modulate blinds to provide sufficient daylight for at least the first 6 m, while effectively shading and eliminating glare

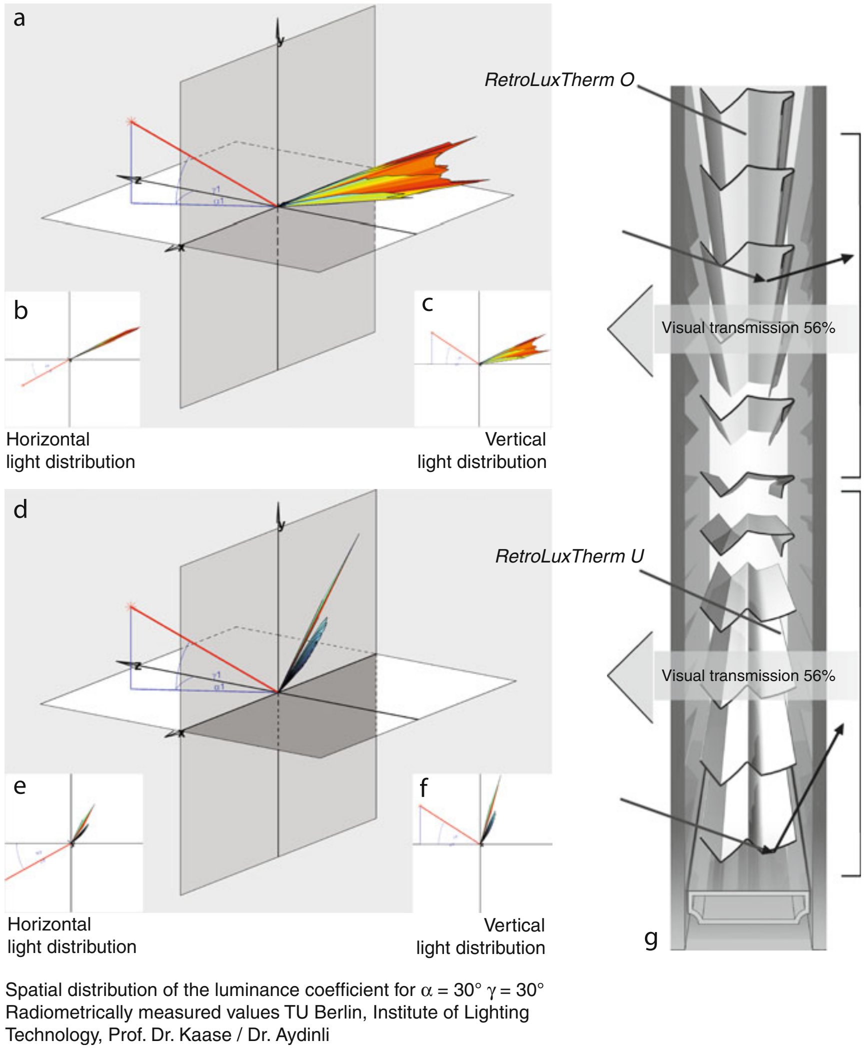
Daylighting Controls, Performance and Global Impacts. Photo 26
View out of RetroFlex blinds in active sun protection position for β = 13



Daylighting Controls, Performance and Global Impacts. Photo 27
(**a**) Light irradiation as a false-color rendering – without redirected light: excessive overexposure (**b**) with redirected light: indirect daylighting (dimmed to comfortable level)

- To modulate blinds to reduce the luminance of the window to a comfortable level to ensure both quality views and daylight transmission
- To modulate blinds to reflect out direct solar energy through mirroring in summer, while simultaneously redirecting a percent of the diffuse sky into the interior
- To modulate blinds to reflect in direct solar energy through mirroring in winter, ideally to thermally absorptive surfaces
- To infill electric light when and where daylight is inadequate for the task

To optimize the integration of daylight and electric lighting controls, at least one major source of electric lighting should shine from the window into the room. This is perfectly possible by integrating the luminous flux and arranging an asymmetrical luminaire with indirect lighting at the height of the window header (Photo 28). This ensures that the bottom sides of the



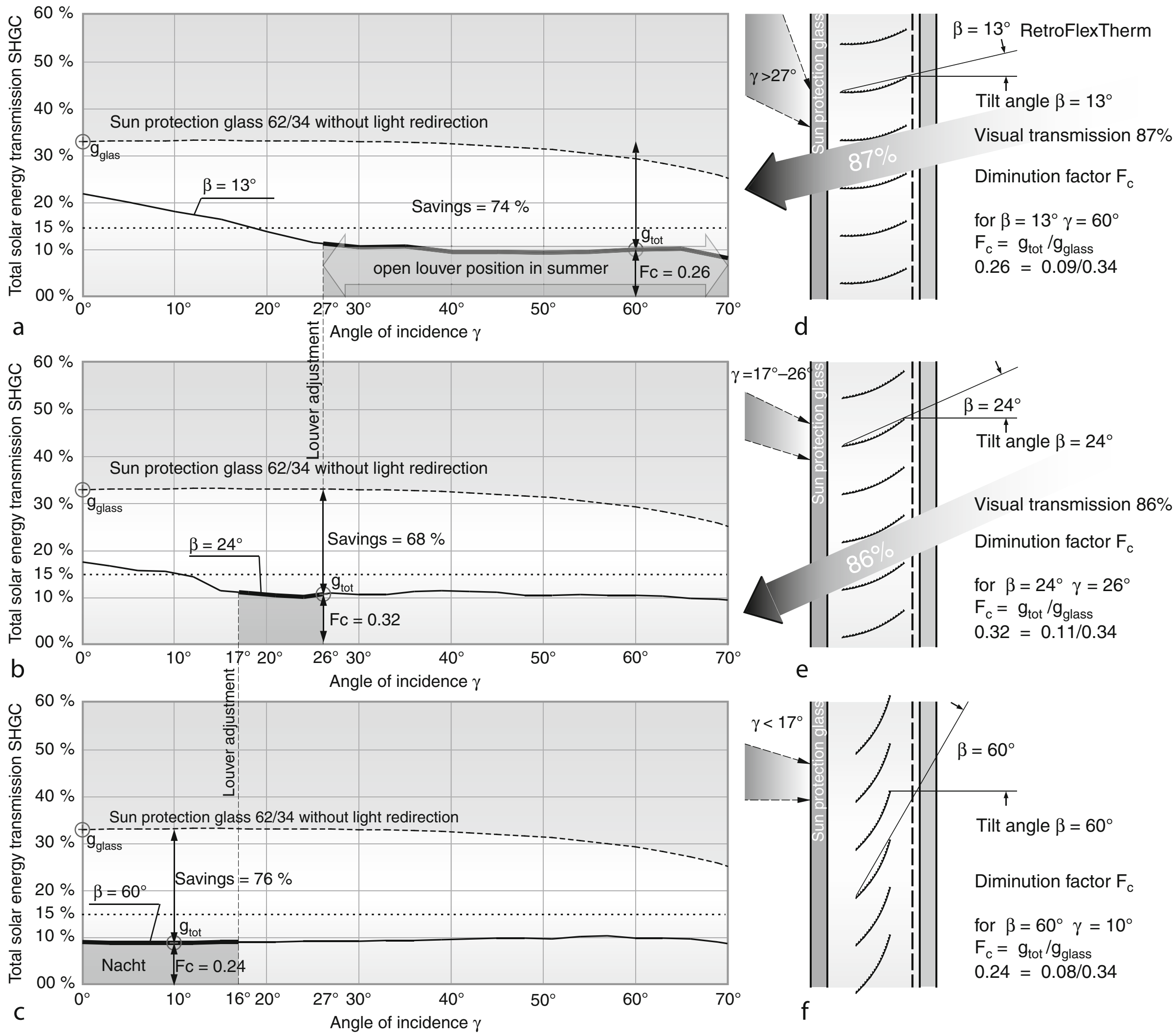
Daylighting Controls, Performance and Global Impacts. Figure 24
Macrostructured louver "RetroLux Therm" in insulation glazing. Analysis of light distribution to the inside for illumination into the depth of the room (type O) (Fig. 24a) and toward the ceiling in the lower window section (type U) (Fig. 24d)

daylight redirection louvers are also used to redirect the electric lighting. The resulting integration of redirected daylight and electric lighting is symbiotic (Photo 31).

Quality Assurance in Daylighting Design

Both simulation and measurement techniques are critical for ensuring the highest level of daylight quality, solar heat management and views. Potential sources of error to be avoided include:

- Inappropriate louver geometry with required daylight reflected externally, without depth internally, or between the louvers themselves resulting in a rise in temperature due to absorption
- Inappropriate reflection characteristics of the surfaces with excessive absorption of heat and light
- Inappropriate louver control for time of day and seasonal variations
- Inappropriate electric lighting control to maximize the use of daylight
- Excessively dark glazing



Daylighting Controls, Performance and Global Impacts. Figure 25
SHGC value analysis of a RetroFlex type blind (Fig. 25d–f) with microstructured louvers (fresnel optics) adjusted in two positions

Having looked at light redirection systems from a functional point of view, the question now arises as to their quantitative effectiveness as thermal and light management systems.

For a quantitative analysis of energy flows for heat and light it is important also to consider the totality of the glazing system including the light redirection system. Depending on the installation position of the light redirection system either before, behind, or in between the glass, there are complex, physical processes taking place between the light redirection system and the glazing, including echo reflections in the glass, absorption, heat build-up, etc. Daylighting calculation methods [6] often provide incorrect results, as they fail to consider the light redirection performance of the contoured louvers. For this reason, it is invaluable to physically measure the light and heat transmission of the overall glazing/light redirection system using calorimetric and radiometric measuring methods.

Daylighting Controls, Performance and Global Impacts. Figure 26
RetroTop louvers have a microprism-structured surface. Used as a light ceiling parallel to the façade, they redirect both the electric light and daylight. The microstructuring of the RetroTop ceiling also provides for superior acoustic baffling boosted by louvers mounted in a freely oscillating system. By providing the louvers with water-filled tubes, the ceiling becomes a highly effective cooling system whose surface, enlarged through microstructuring, has a cooling effect as it absorbs heat

Daylighting Controls, Performance and Global Impacts. Photo 28
Light redirected through RetroFlex-blinds. To prevent overheating and overillumination only 2–3% of the solar irradiance is redirected onto the ceiling creating 500 lx in 7 m of room depth

Calorimetric methods measure the electric energy required to keep a heat sink installed behind the window assembly at a constant temperature, and translate the results into the heat transfer of the system (SHGC or g-value). It combines measurement with calculation, given a set of tolerances, which is why measurements using the same window assembly may result in different SHGC values from different institutes.

Radiometric measurements are taken under an artificial sun. These measurements are highly accurate and easy to perform. Parameters measured include the

Daylighting Controls, Performance and Global Impacts. Photo 29
The light deflected from the façade to the ceiling is redirected in a conical shape onto the workplace through the concave design of the louvers. This ensures excellent illumination of the workplaces with glare-free top and side light

Daylighting Controls, Performance and Global Impacts. Photo 30
The light deflected from the façade to the ceiling is redirected in a conical shape onto the workplace through the concave design of the louvers. This ensures excellent illumination of the workplaces with glare-free top and side light

wavelengths of the transmitted irradiation, from which the SHGC, or g-value is calculated (Fig. 30). Radiometric measurements can also determine the light distribution (LDC) of the glazing/light redirection system into the interior for different sun altitude and azimuth angles (Figs. 22, 24, 30).

According to DIN 4108–2, the effectiveness of a sun protection system is described using the diminution factor F_C. The total solar energy transmission of a glazed façade is thus calculated using the following equation:

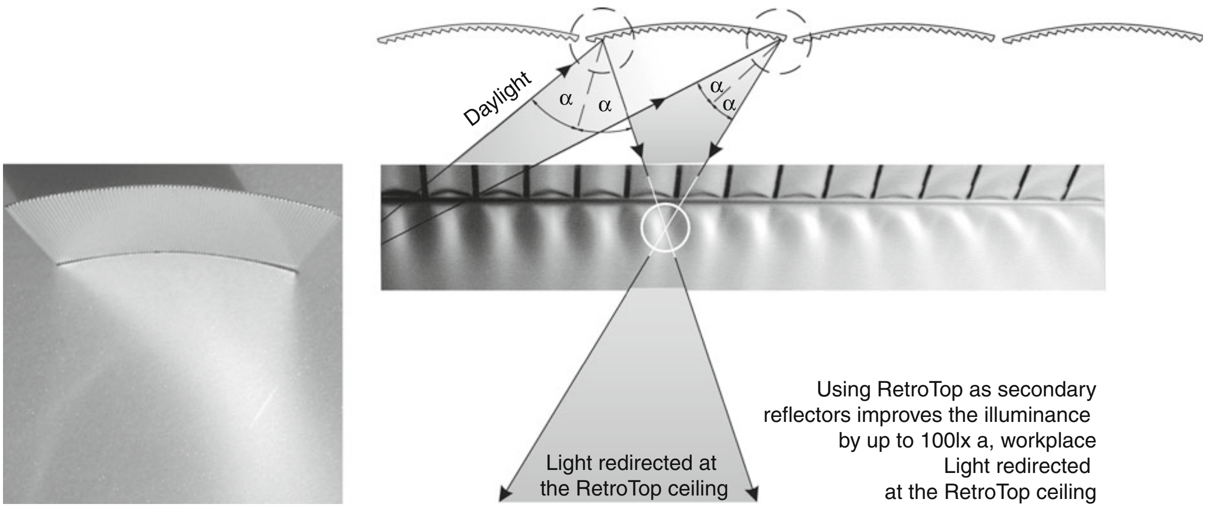
$$g_{tot} = F_C \times g_{glass}$$

g_{tot} – Total solar energy transmission through glazing including sun protection

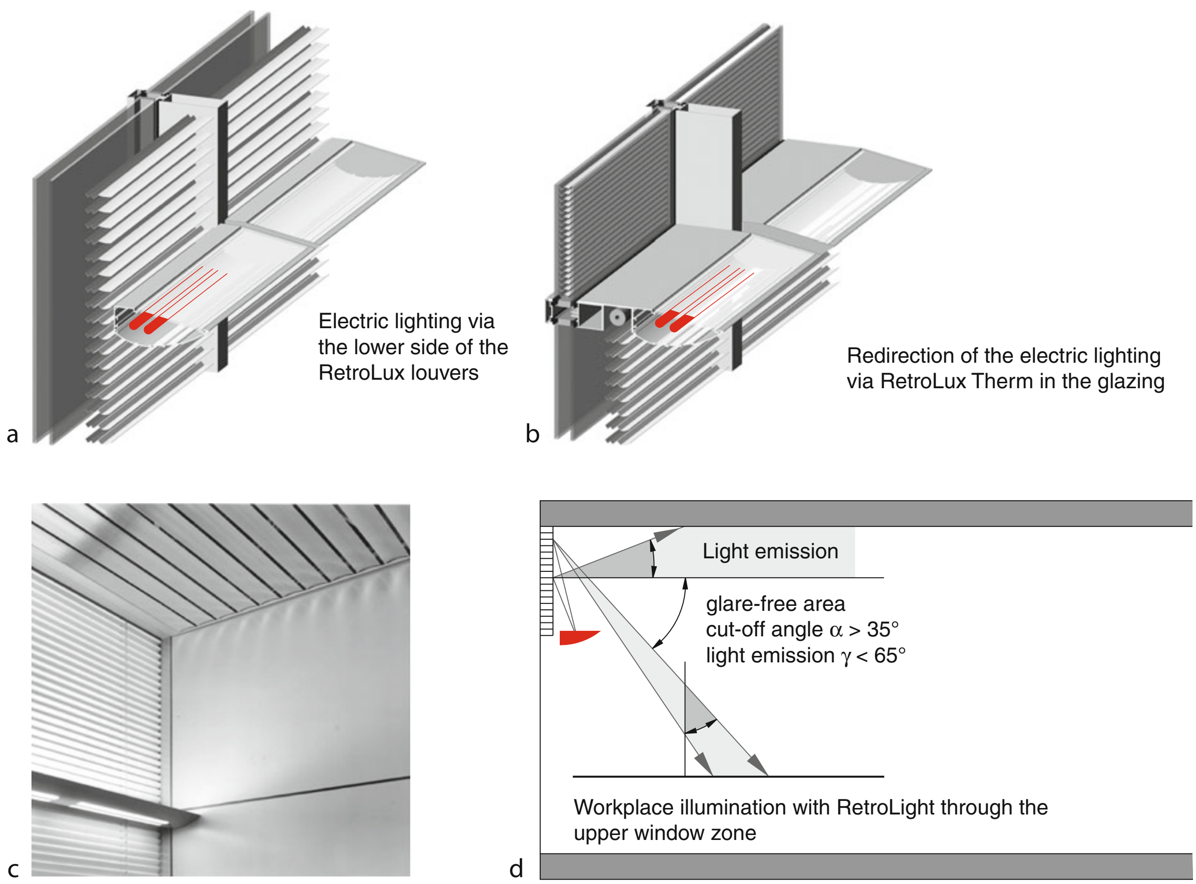
g_{glass} – g-value of the glazing

F_C – Diminution factor of the sun protection system

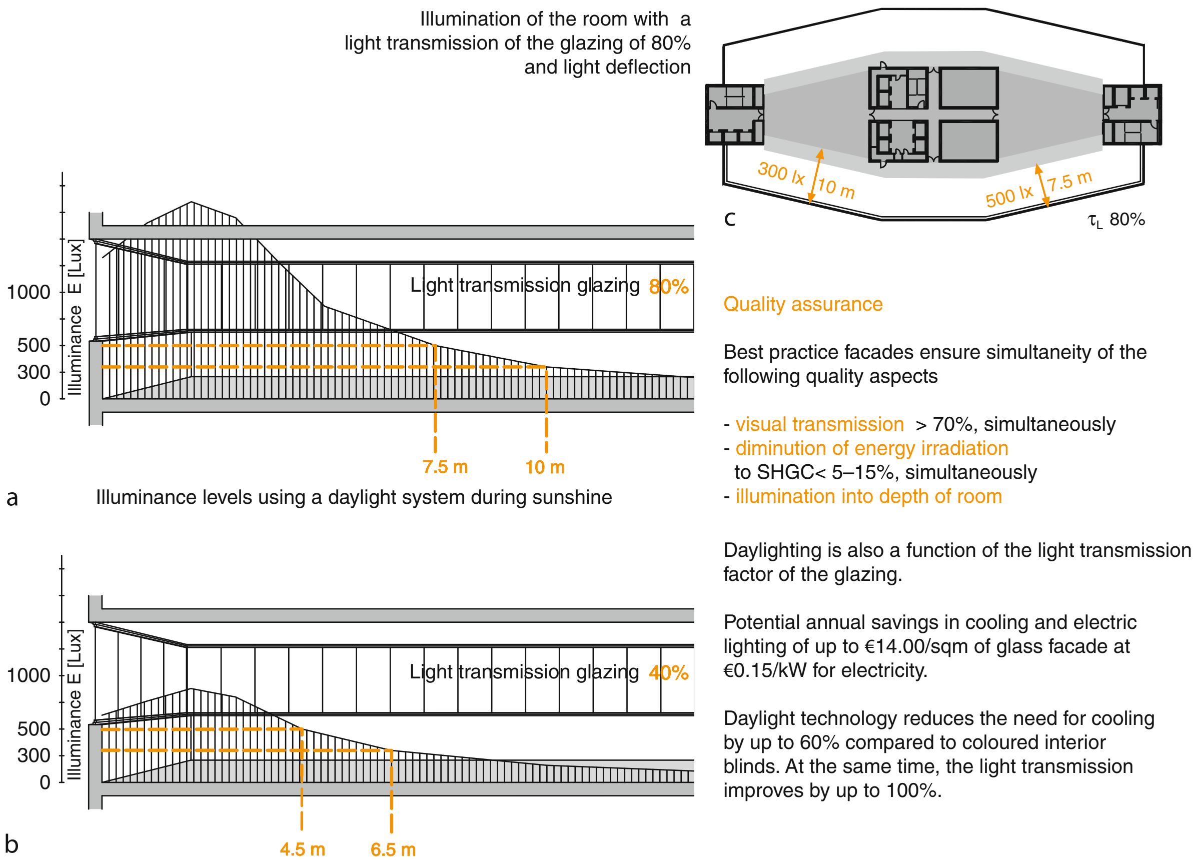
This calculation, however, is not sufficient for quality assurance of the façade design since it is focused on the thermal performance of the window relative to sunshine (Fig. 31). Best thermal performance of the façade will ensure low temperatures of the glazing (Fig. 32). However, windows are critical to effective



Daylighting Controls, Performance and Global Impacts. Figure 27
Light redirected by ceiling elements. Ceiling louvers with microprism-structured mirrors deflect the indirect daylight redirected toward the ceiling vertically onto the workplace



Daylighting Controls, Performance and Global Impacts. Figure 28
Electric lighting and daylight system optically integrated [EP 0461137; US P 5293305]



Daylighting Controls, Performance and Global Impacts. Figure 29
Comparison of illumination into the depth of room using a daylight redirection system for glazing with a light transmission of 40% and 80%, respectively

daylighting, a factor that trumps cooling, so light transmission is equally important for consideration. The balance of solar heat and light is taken into account in the latest DIN EN 13363 standard – yet still without consideration of light-redirecting blinds, especially those that can distinguish high and low sun angle sunshine.

Windows have the additional goal of providing views, visual connections with the landscape and life on the ground plane. While very low solar heat gain factors are easy to achieve with highly reflective glass, or window assemblies that assume shades to be predominantly closed, these windows no longer ensure the views and daylight critical to building occupants (Photos 21, 22, 24, 26, 32). As a result, all calculations should assume that blinds are in an adequately open position to ensure views and daylight effectiveness.

To evaluate the quality of the window assembly for thermal and visual performance, the g-value (SHGC) parameters must be complemented by light transmission and view clarity parameters. In other words, the g-value must be differentiated as a combined value of energy transmission for short-wave light radiation and long-wave heat radiation components. In the USA, a light to solar gain ratio (LSGR) has been introduced to give value to daylighting and views in relation to shading in the selection of glazing assemblies.

Daylighting Controls, Performance and Global Impacts. Photo 31
Night Architecture using RetroLight, municipal works, Bochum, Germany, Architects: Gattermann + Schossig, Cologne

It is important to note that while glazing assemblies may be evaluated by combined values of daylight and view as well as shade, many internal and external layers – shade, louvers, overhangs – are not evaluated for their impact on daylighting. In addition, there are many climate periods when solar heat gain is desirable, such that dynamic properties for the entire window assembly are ideal.

Conclusion

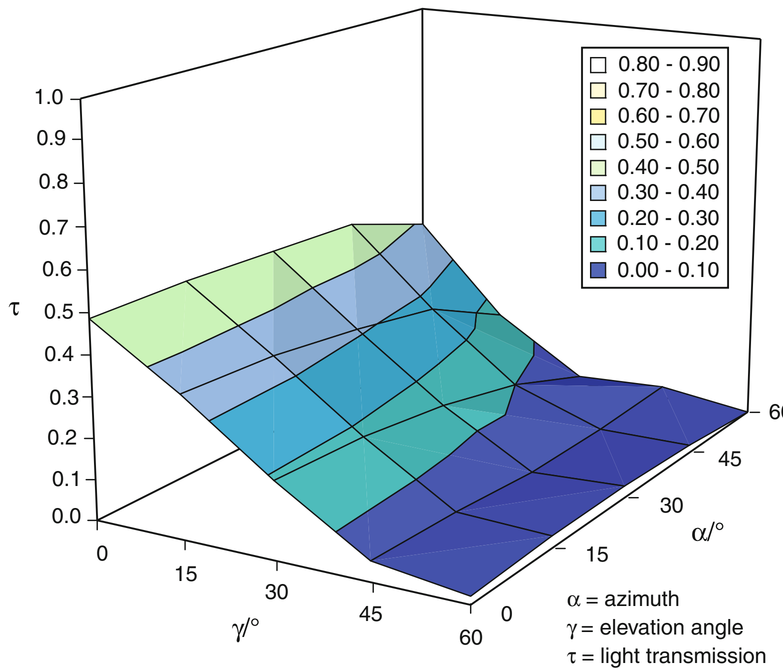
Daylight and Solar Managing Façades as a Focal Point for Building Energy Futures

The largest primary energy load in buildings is for lighting, mostly during the daytime. The most rapidly increasing primary energy load in buildings is for cooling. This is where daylight technology offers the greatest opportunity for the design and engineering community. It not only reduces or manages the external solar load, but also eliminates the electric lighting load during the daytime along with the associated cooling loads.

Integrated design is critical to the detailing of façades for effective daylight and solar energy management. An interdisciplinary process can ensure that it meets a wide range of design goals. To date, it has been common practice in Europe to independently design sun shades and glare protection in different layers inside and outside the building. The design of fixtures to diffuse light does not consider daylight. Structural design is typically independent of light or thermal design. Interior space layout and ceiling design is independent of daylight and often thermal conditioning. Breaking the building components into individual functional elements frequently led to excessive efforts and significant cost increases in the construction. Integrated design engages the architect, the lighting/daylighting designer, the mechanical engineer, and even the structural engineer in synergistic innovation (Figs. 33–37).

University curriculum must be revised to recognize the importance of integrated design. Every architect should be taught to be effective "system integrators," capable of orchestrating an interactive process that engages the expertise of the mix of disciplines early in the design process for maximizing synergistic innovation. An effective integrator must have a core competency in building physics, climate and energy management, and the full set of building technologies that impact heat, light, air, sound, and structural integrity – with the building façade and adjacent interiors as a primary focus for a sustainable future.

At the graduate level, universities must also take a far more proactive role in research related to daylighting technologies and system integration. The optical research inherent in fixtures that manage point light sources and linear light sources have not yet been applied to planar light sources such as a window. The geometry and positioning of light reflectors (internal, external, between glass installations) and critical dynamics given climate and time of day variations are



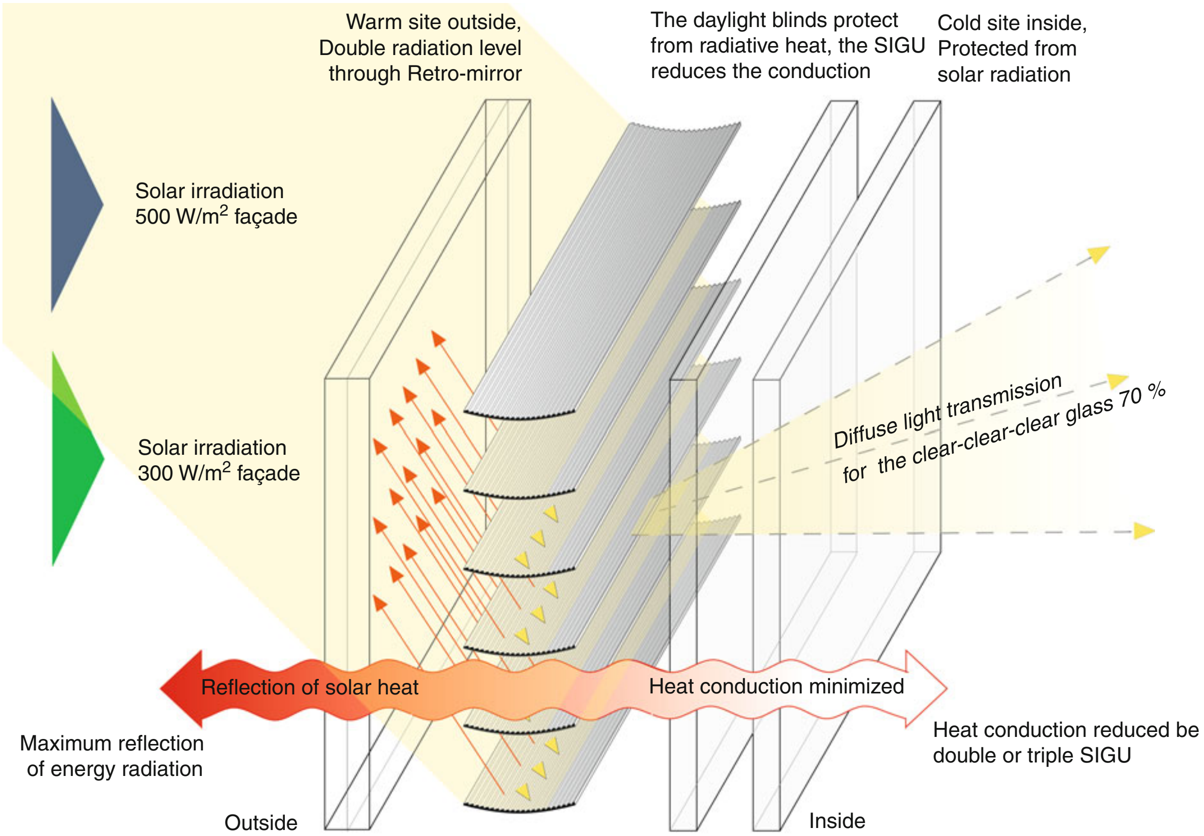
Daylighting Controls, Performance and Global Impacts. Figure 30
Example to illustrate the light transmittance τ for RetroLux Therm O with type 63/32 solar protection glazing (see also Fig. 24)

critical areas of scientific and technical innovation. The interaction between glass coatings, such as reflective enhancing PVD coatings, and mirror systems, such as semi-specular, lacquered or anodized surfaces, offer enormous potential for the research and manufacturing community.

For the design community, algorithms and computational tools need to be developed to calculate the bidirectional energy- and light transmission values for dynamic tilt positions of the special mirror contours with reference to the positions of the sun. Existing simulation tools must be refined beyond qualitative transmission data, to describe the optical properties of reflected light to calculate the effectiveness of daylighting for different sky and room conditions. Tools that accurately quantify annual and peak lighting, heating and cooling energy savings, and quantify the carbon benefits will be critical for designers as well as policy makers. Then standards such as DIN EN 13363–1 and 13363–2 [7] need to be refined to reflect the full energetic behavior of façades.

Appendix A. Daylight redirection-systems patents [excerpt]: Dr-Ing. Helmut Köster

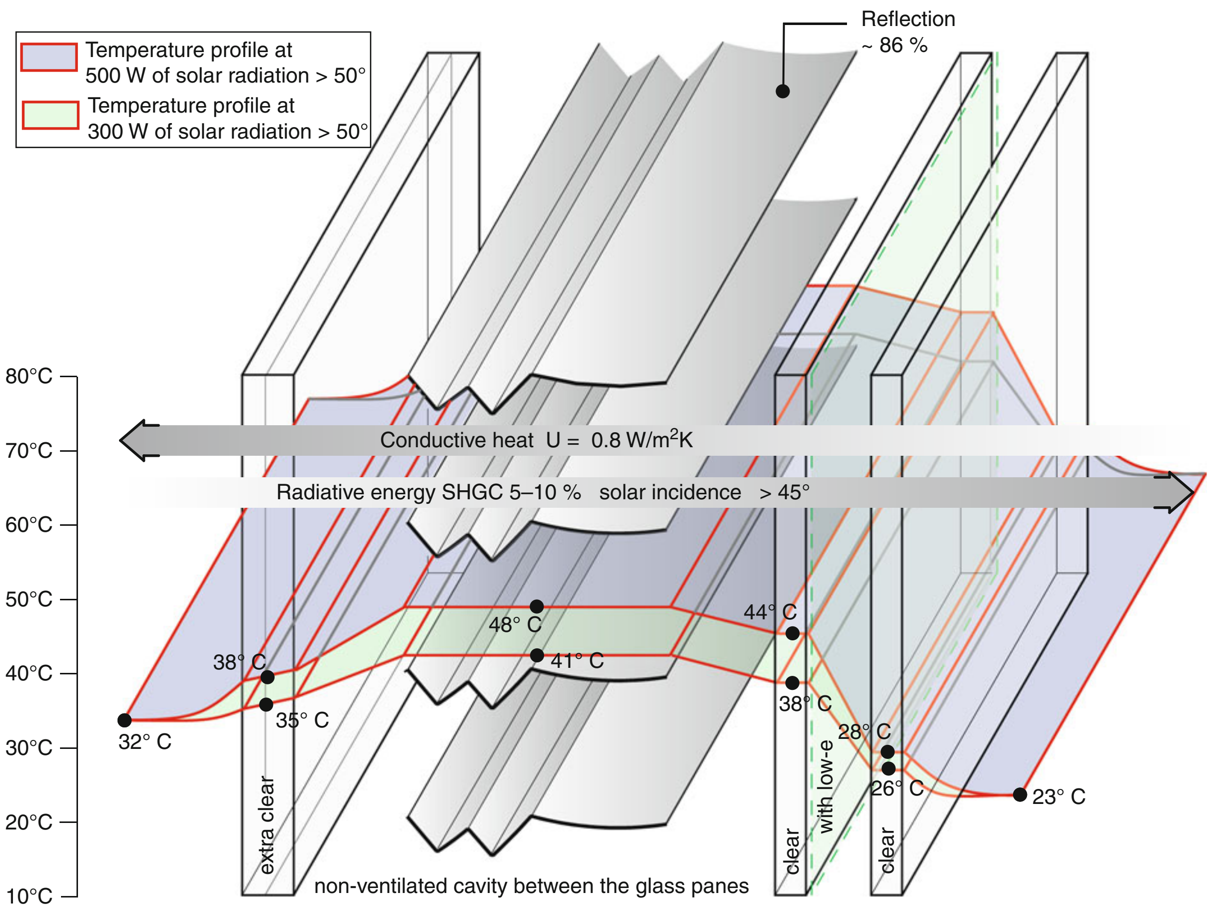
EP 0793 761	Stepped Lamella for guiding Light Radiation
DE P 69514 005.1-08	Stepped Lamella for guiding Light Radiation
CH EP 0 793 761	Stepped Lamella for guiding Light Radiation
IT (EP) 0 793 761	Stepped Lamella for guiding Light Radiation
Fr (EP) 0 793 761	Stepped Lamella for guiding Light Radiation



Daylighting Controls, Performance and Global Impacts. Figure 31
Example of optimized façade construction with a closed cavity: the outer pane is exposed to a double radiation load by incident and retroreflected sun. The outer pane should, therefore, be made from low-iron, color-neutral glass to prevent absorption and heat generation. The lower the temperature of the outer glazing is, the lower the heat radiation between the louvers will be on the inner glazing. The better the reflectivity of the light redirecting louvers is, the lower the heat-up of the air space will be

GB EP 0 793 761	Stepped Lamella for guiding Light Radiation
NL (EP) 0 793 761	Lamelles en Gradins Destinees au Guidage de Rayonnement Lumineux
AT EP E 187 800	Stepped Lamella for guiding Light Radiation
AU P 704 884	Stepped Lamella for guiding Light Radiation
CA P 2 205 560	Stepped Lamella for guiding Light Radiation

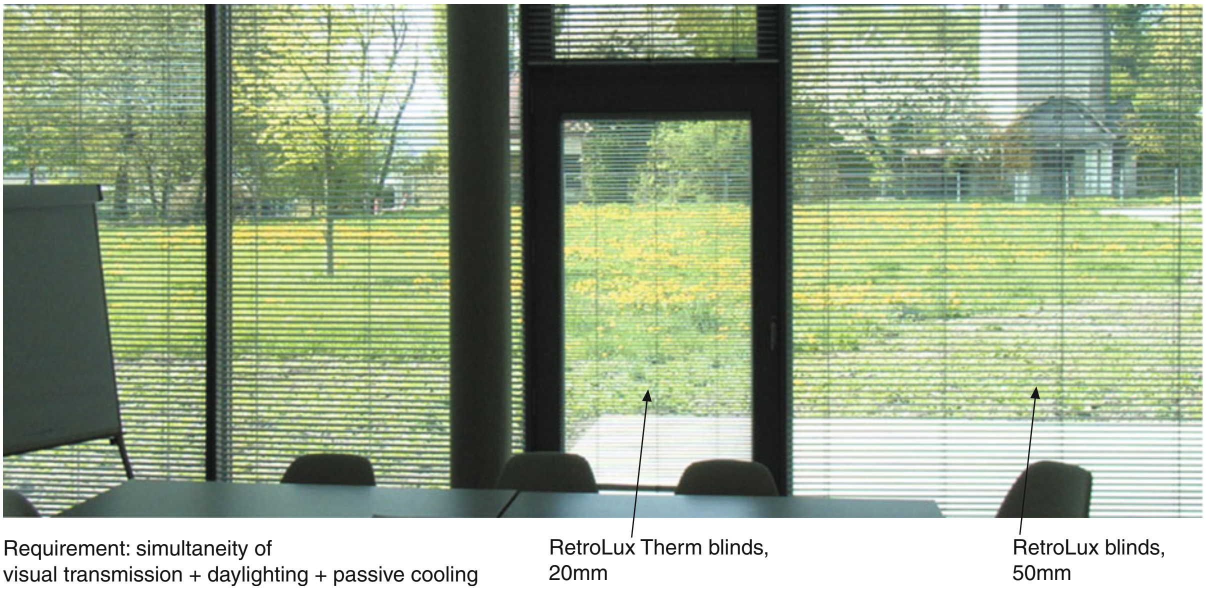
US 6,240,999	Stepped Lamella for guiding Light Radiation
EP 0461 137 B1	Lichtlenksystem für die Beleuchtung eines Innenraumes
DE P 590 09 101.8-08	Lichtlenksystem
US P 5 293 305	Light Guidance systems for the illumination of an interior area
USA 6,367,937	Sun Protection Installation.....



Daylighting Controls, Performance and Global Impacts. Figure 32
The above temperature profile in a closed cavity can be reached with RetroLux or RetroFlex blinds at angles of incidence >45°. The contour of the blinds is of crucial importance, because the low temperatures can be realized even in a horizontal louver position. Simultaneously a visual transmission of 70–80% between the louvers and the desired improved daylighting is achieved. The temperatures in the cavity should not exceed 60°C to ensure the longevity of the motors, plastic parts, and fibers

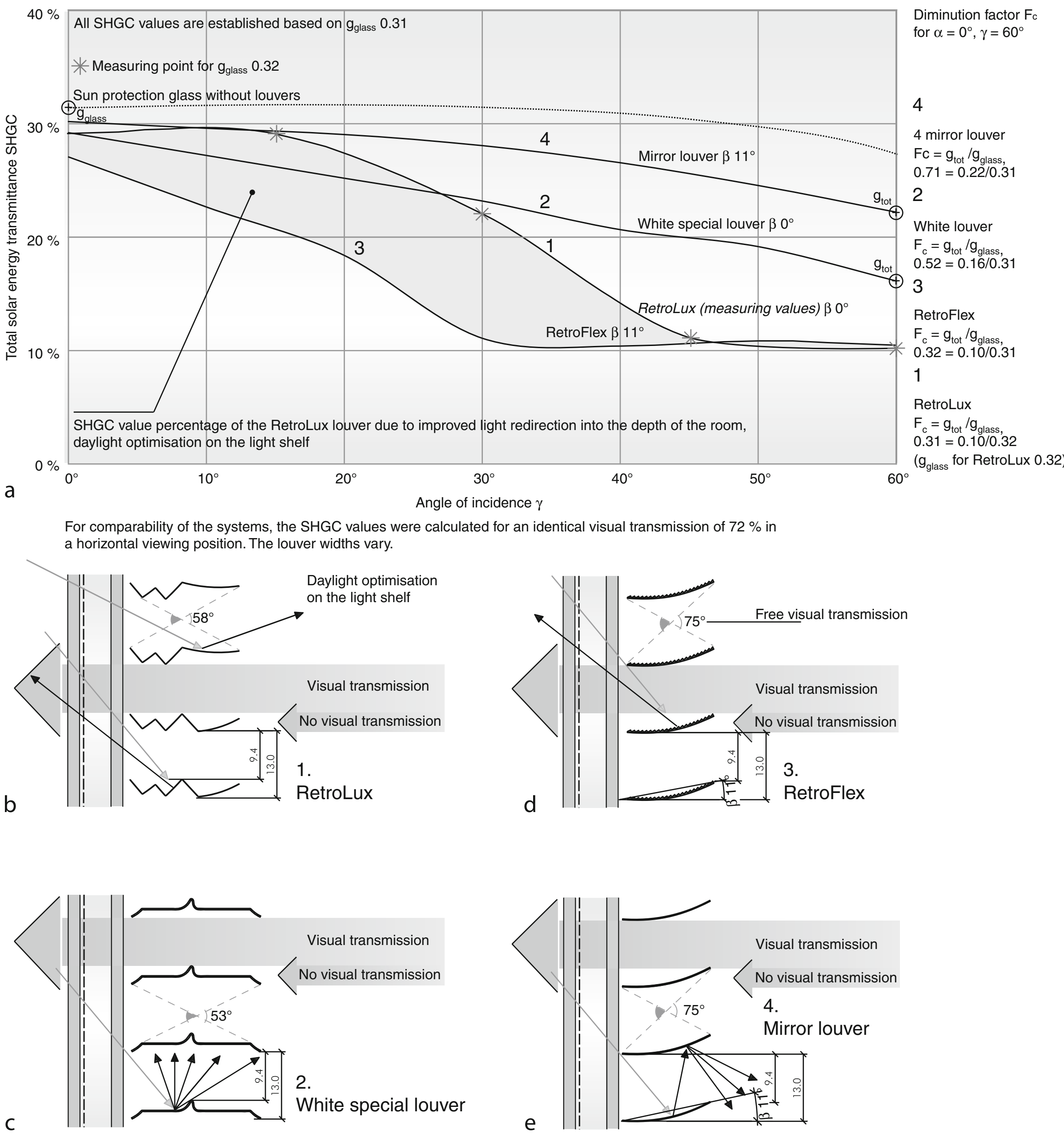
AT 411613	Sonnenschutzanlage mit Sonnenschutzlamellen.......
CH 694,947	Sonnenschutzanlage mit Sonnenschutzlamellen.......
NL 1010766	Zonwering met zonweringlamellen.....
GB 2332229	Sun Protection Installation.....
FR 9815482	Sun Protection Installation.....

IT - 1303650	Impianto di Protezione contra....
CA 2,255,302	Sun Protection Installation.....
AU 756628	Sun Protection Installation.....
AU 643429	Light deflecting system.....
DE 100 2006 006 855.6	Bewegliche Fixierung leiterartiger Bauelemente
DE 10 2005 028 6550	Medienfassade

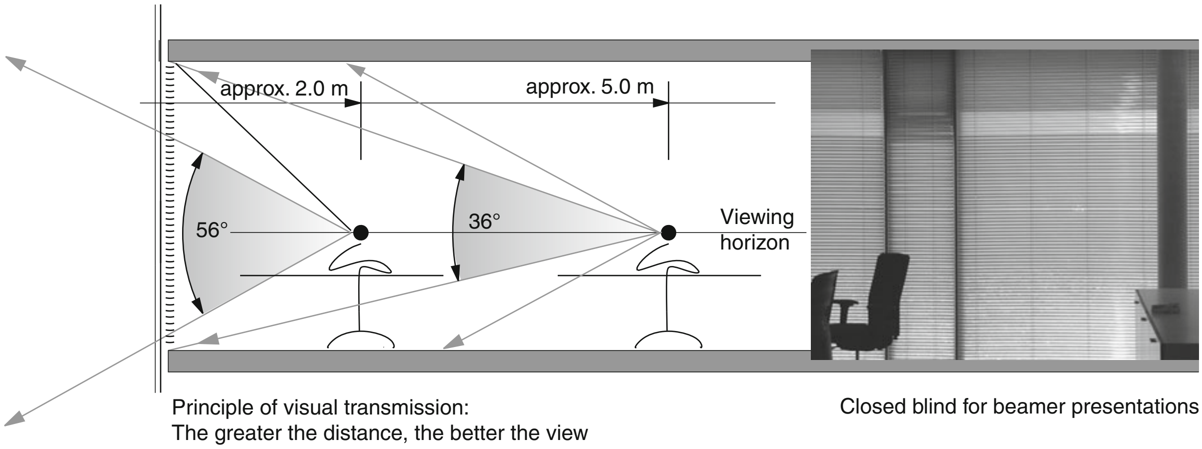


Daylighting Controls, Performance and Global Impacts. Photo 32
Visual transmission of RetroLux

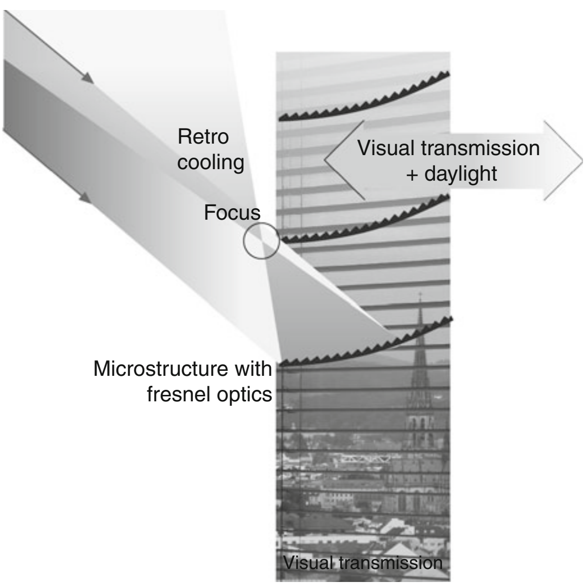
Daylighting Controls, Performance and Global Impacts. Photo 33
The Sopharma and Litex buildings in Sofia have a non-ventilated double-skin façade with a closed cavity (see Fig. 31) and RetroFlex blinds. The room temperature does not exceed 26°C even without chilling even at outside temperatures of 35°C and sunshine



Daylighting Controls, Performance and Global Impacts. Figure 33
This illustration shows the dynamic SHGC values of different types of louvers based on condition of the same visual transmission for different angles of incidence. The mirror louver (Fig. 33e) performs very poorly, as the sun is reflected onto the gray lower side where it is absorbed and converted into heat. The white louver (Fig. 33c) shows better thermal properties. The RetroLux louvers (Fig. 33b) with light shelves in the second section produce a good light output with an excellent passive cooling capacity in the high summer sun. Despite open position, the RetroFlex louvers actively provide passive cooling even when the sun is low (Fig. 33d)



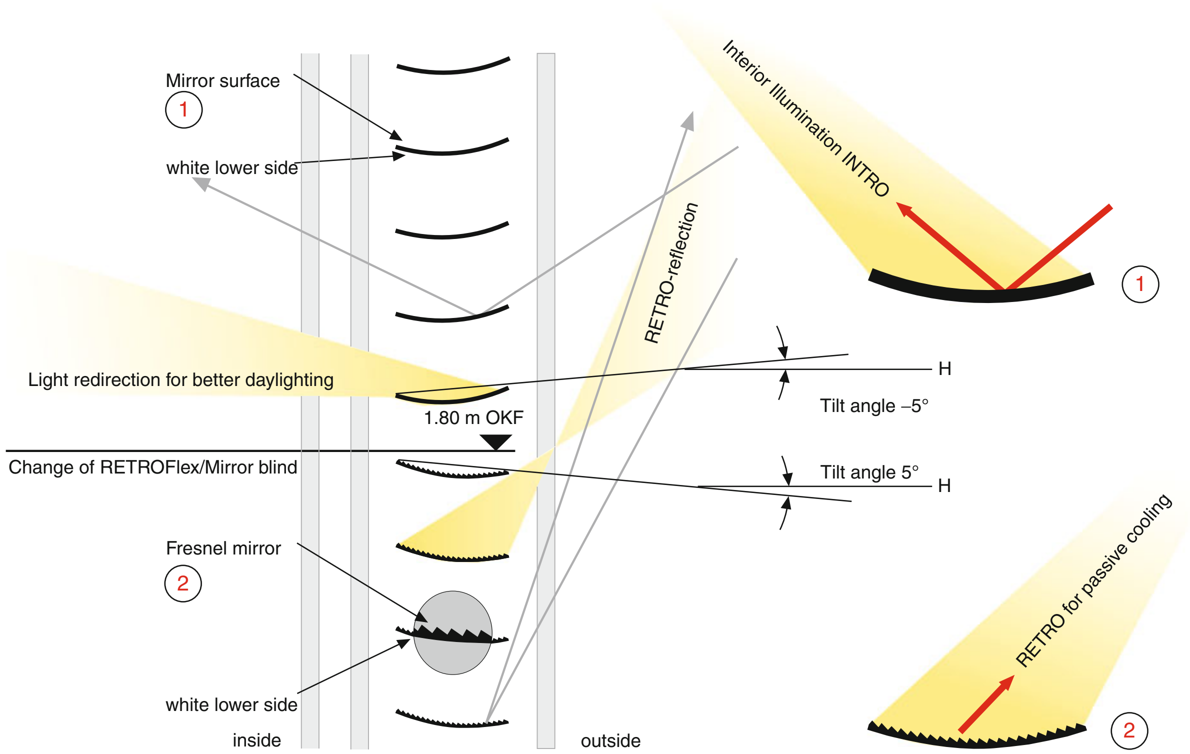
Daylighting Controls, Performance and Global Impacts. Figure 34
Analysis of visual transparency for RetroLux and RetroLux Therm during active protection from the high summer sun and closed blinds



Daylighting Controls, Performance and Global Impacts. Figure 35
Visual transmission through RetroFlex louvers 74–80% (see also Figs. 17, 18)

DE 102 60 711	Blendfreie Jalousien
DE 100 18 451	Herstellung von linearen, prismatischen Strukturen auf einem lamellenartigen Festkörper

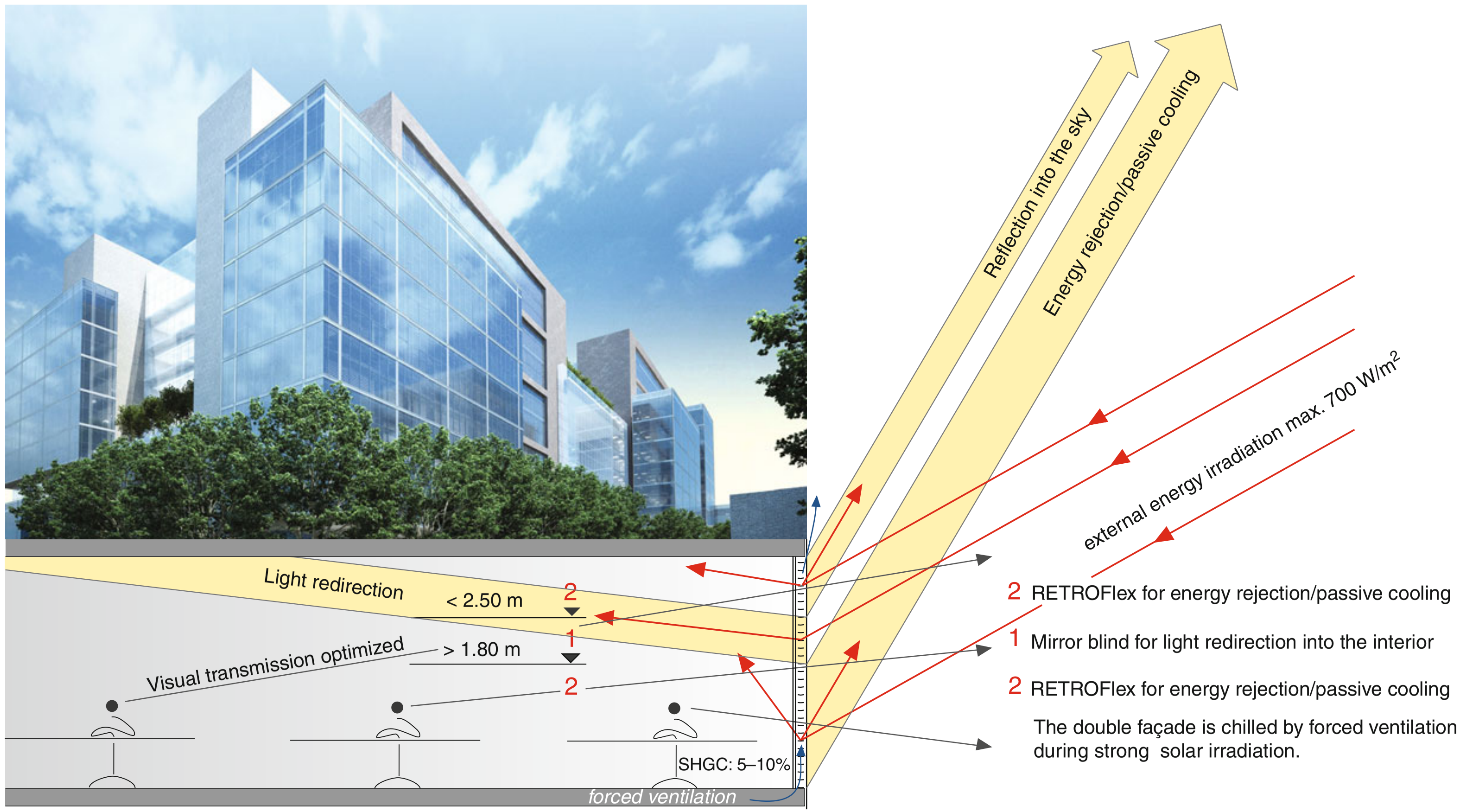
DE 198 28 543	Sonnenschutzanlage für Sonnenschutzlamellen, die eine gezahnte Oberseite aufweisen
DE 196 36 817	Sonnenschutzanlage mit Sonnen- schutzlamellen, die eine gezahnte Oberseite aufweisen
DE 44 42 870	Jalousielamelle zur präzisen Steuerung der direkten Sonneneinstrahlung
DE 000 331 483 -0001	Oberfläche für Jalousielamellem _ Oberfläche mirkostrukturiert, gezahnt
M9502488.3	Jalousie zur Tageslichtumlenkung
000 334 483 Alicante	selbst gefertigtes Lamellenprofil Retroflex
DE 401 04 706.7	Fassadenpfostenausbildung vorzugsweise für Glasfassaden mit und ohne Leuchte
DE 401 06 175.2	Lichtlenkdecken (1 Muster)
DE 401 09 455.3	Asymetrisch strahlendes Leuchtenmodul
DE 401 10 472.9	Oberlichtleuchte von Trennwänden



Daylighting Controls, Performance and Global Impacts. Figure 36
Strategy: within the retroreflective RetroFlex curtain a few mirror blinds with opposite qualities may be inserted in the upper window part to illuminate the working area in large depth (see also Fig. 37)

DE 402 02 313.7	Leuchten
DE 402 02 431.1	Trennwandleuchte II
DE 402 03 978	Lichtlenkjalousien bzw. Lichtlenkvorrichtung
DE 402 10 688	Jalousiebehang
DE 403 04 242	Lamellenvorhänge
DE 404 04 133.7	Lamellenvorhänge
M 9502488.3	Jalousie zur Tageslichtumlenkung
DM/052988 (15)	Blinds for reflecting sun and diffuse daylight as well as artificial light (2 x Retroluxtherm)

EP 00951306.0erteilt als EP 1212508	gezahnte Tageslichtlamelle
PCT/EP00/05929Intern. Application No.	gezahnte Tageslichtlamelle, toothed daylight blinds
CA 2,377,711	Toothed Daylight Blinds
USA 6,845,805	Toothed Daylight Blinds
AU 758 794	Toothed Daylight Blinds
EP 2006 005909	Medienfassade
PCT/EP2006/ 005909International Application No.	Medienfassade, s. auch, EP Anmeldenummer 06015154.5



Daylighting Controls, Performance and Global Impacts. Figure 37
In the Standard Bank in Johannesburg, South Africa, the window is structured in three functional sections (see Fig. 36) with opposite values to ensure best daylighting in larger depths of the room without overheating

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Facades and Enclosures, Building for Sustainability

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Article Outline

Glossary

Facade enclosure envelope Throughout this entry, Facade is a subset of Enclosure and Enclosure is considered the same as Envelope.

Carbon neutral net-zero and the 2030 challenge Carbon-neutral buildings and net-zero buildings are typically defined as buildings designed to achieve net-zero in green house gas emissions during their lifetime. This has been set as a requirement for all new buildings by 2030 in the 2030 Challenge™ (url).

Passive survivability Environmental Building News uses the term passive survivability to describe a building's ability to maintain critical life-support conditions in the event of extended loss of power, heating fuel, or water, or in the event of extraordinary heat spells.

Biophilia Introduced by E.O. Wilson, the biophilia hypothesis suggests that there is an instinctive bond between human beings and other living systems that must be met by buildings that ensure critical connections.

Ambient and task lighting Ambient lighting is the light needed for safe movement and non-visual tasks, while task lighting is linked to visual acuity at task and must be glare-free. Daylight can be used for both, but requires significantly greater design resolution for task lighting.

Mixed-mode or Hybrid HVAC An approach to space conditioning that combines natural ventilation from operable windows or vents with mechanical heating, cooling, and ventilation systems (HVAC).

Night ventilation An approach to space conditioning that utilizes cool night air to precool the buildings' thermal mass in order to reduce daytime cooling demands.

Thermal bridge A conductive or non-insulated element in the facade assembly that allows heat to be unnecessarily lost or gained, and allows condensation to occur, to be addressed by well-designed thermal breaks.

PassivHaus™ A standard that codifies energy conservation and passive conditioning requirements for residential and small commercial buildings.

Double envelope The introduction of two facades with a captured air space and static or dynamic components that support orientation- and season-specific modulation of climate conditions.

Rainscreen An independent layer on the facade to manage weather challenges, separated by vent spaces from the structural, thermal, and vapor management of the primary facade.

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Robert A. Meyers (ed.) Encyclopedia of Sustainability Science and Technology, © 2012, DOI 10.1007/978-1-4419-0851-3

Definition of the Subject

Sustainable buildings have enclosures that ensure the highest level of thermal, visual, acoustic, and air quality, as well as design for change, through system flexibility, and for long-term building integrity (Fig. 1). Sustainable enclosure design clearly demonstrates advances in enclosure components and assembly design, as well as their effective integration with interior systems, structural systems, mechanical conditioning systems, lighting systems, telecommunications and power systems. Sustainable enclosures effectively address ten major responsibilities, indeed areas of major innovative opportunity, in the pursuit of aesthetics, comfort, and resource conservation:

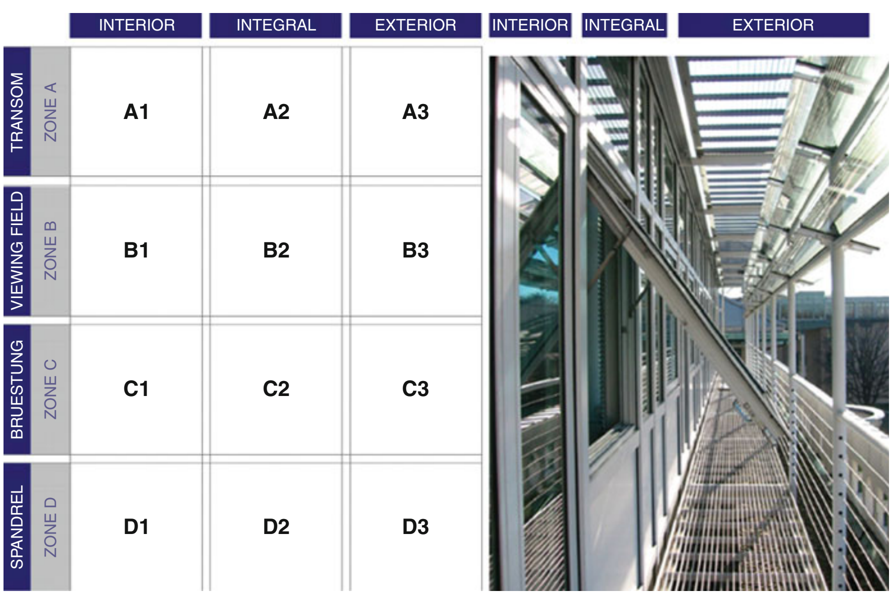
1. Access to the natural environment
2. Daylighting
3. Natural ventilation
4. Heat loss/heat gain control
5. Solar control
6. Load balancing
7. Passive and active solar
8. Water
9. Enclosure life
10. Systems integration

In addition to performance goals for building roofs and exposed floors, the design of high-performance building enclosures must fully resolve at least 12 facade layers: the transom, viewing field, kick plate, and spandrel (top to bottom) and the interior, integral and exterior layers (inside to out) to resolve each of the 10 performance goals (The relative importance of facade components and layers to each performance outcome will be highlighted in graphics with deepest shading for the most important design decisions.)

Introduction

Architecture Unplugged: Superefficient Buildings that Environmentally Surf

Carbon-neutral buildings, net-zero buildings, and the 2030 challenge. To meet these goals, the next generation of buildings must be designed to use so little energy that on-site renewable energy can fully meet the



Facades and Enclosures, Building for Sustainability. Figure 1
Diagram illustrating 12 areas in the facade critical to various performance outcomes

heating, cooling, and lighting loads – loads that represent over 35% of all US energy.

For the first generation of projects, these challenges are being met by tight buildings, with superefficient equipment, fed in part by solar installations. While this will help ensure a 30% reduction, it will never achieve carbon neutrality .

Carbon neutrality is critically dependent on the maximum use of nature's renewable energies – daylight, natural ventilation, natural cooling, and passive solar heating. Building systems will need to be turned off as long as possible – ensuring buildings that "free-roll" or better yet "environmentally surf" through hours, days, months, and seasons with natural conditioning. The beauty of free-rolling buildings goes beyond energy and carbon, however, to support health, productivity, and a higher quality of life.

The most critical early design decisions relate to building massing – the height, depth, and orientation of buildings – which has a major impact on indoor environmental quality and energy loads. Neither "the tallest building in the world" nor "the largest building under one roof" will offer sustainable work environments in a power failure. Indeed, these buildings create significantly higher-energy loads in almost every climate since they eliminate the use of daylight, natural ventilation, or the natural dissipation of internal heat gains through the building skin [1], and must be abandoned in a power outage. If air quality, comfort, and energy are drivers for building form, then the next generation of buildings will strive toward controlling the building depth, height, and orientation to achieve environmental comfort for a maximum percentage of the year – unplugged.

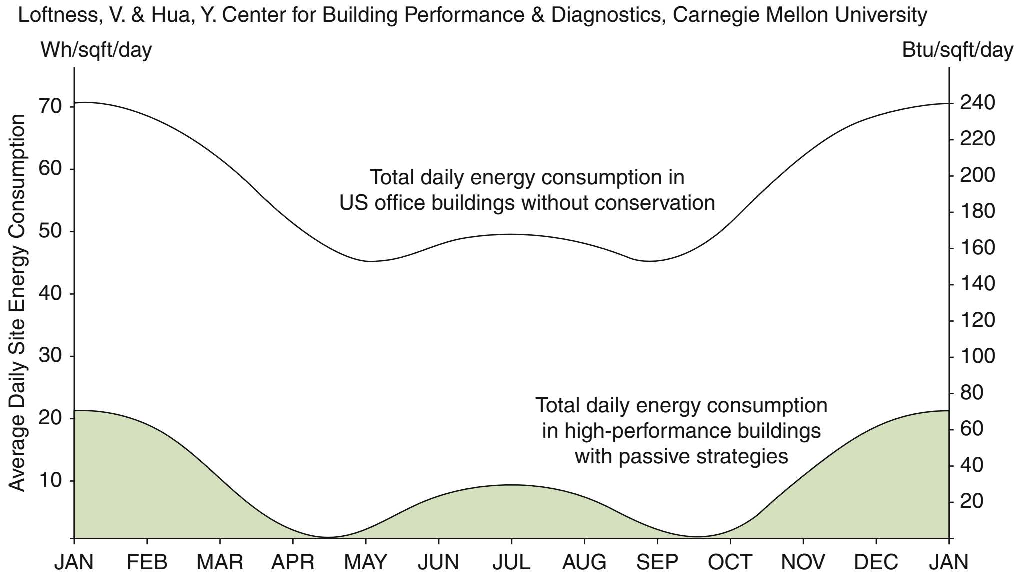
"Architecture Unplugged" would require enclosures that demonstrate serious attention to the management of solar gain, heat transfer, moisture migration, and day-night load balancing – a form of environmental surfing that depends on dynamic facades that recognize time of day, season, and variability of climate. These mass, color, venting, and thermal insulation characteristics are key to energy conservation in buildings, and require entirely regional solutions. Heavy capacitance masonry facades will be seen in desert climates with large diurnal swings; heavily shaded and highly operable facades will be seen in warm, humid climates; and solar exposed yet well-insulated facades will be seen in cold climates. In each climate, the massing, orientation, and selection of facade materials will be regional in character, providing the maximum natural comfort before mechanical systems need to be introduced (Figs. 2 and 3).

Facades that Maximize Individual Access to the Natural Environment

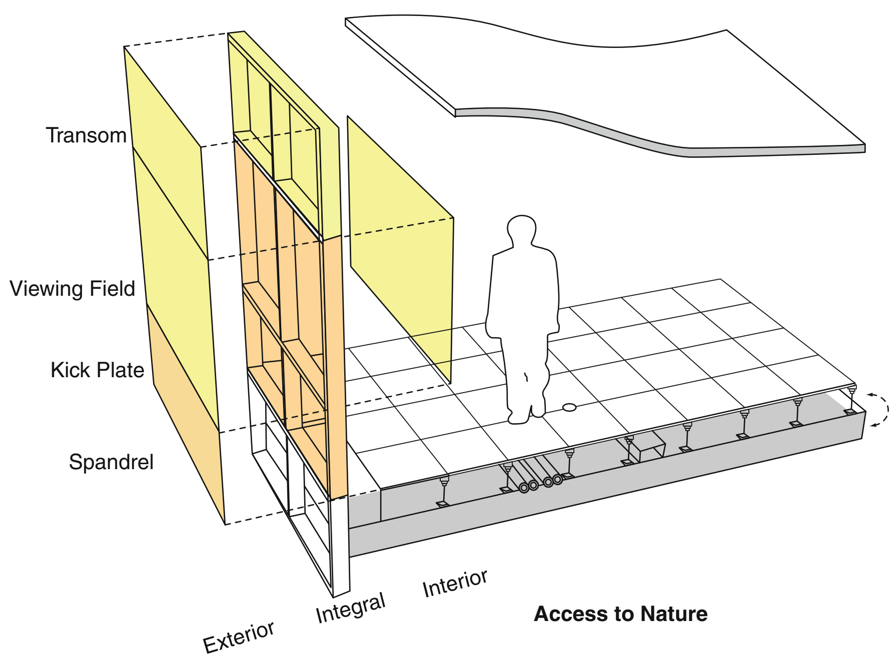
The most significant step that designers, engineers, and building managers can take to move toward healthier and more sustainable buildings is the commitment to increasing individual contact with the outside environment. The emerging field of "biophilia" has identified the importance of access to nature to human well-being [2–5], exploring a range of qualities of the natural environment: views, daylight, sunlight, fresh air, breezes, access to outdoor spaces and activities, circadian rhythms, seasonal and daily climate variations, and nature's sounds, smells and habitat. Windows and doors connect building occupants with a richness that may be critical to individual health. At the same time, windows and doors provide those outside the building with a level of transparency, oversight, and contact that may be critical to community.

Europe and Scandinavia have guaranteed every worker seated access to a window with views, setting a maximum distance of 7 m, or 20 ft from the window wall. In Switzerland and Scandinavia, they have further guaranteed access to *operable* windows in each workplace [6]. With these standards, buildings typically do not exceed 60 ft from window wall to window wall, and always maintain operable, dynamic facades instead of sealed, seasonally unchanging building enclosures.

Driven by the advent of air conditioning and inexpensive electricity, the "obese" buildings of today (maximum volume – minimum surface area buildings) have actually resulted in a dramatic increase in the length of the cooling "season" for buildings in all climates. They have also resulted in a significant increase in lighting loads during daylight hours, in combination often contributing more than 50% of the total energy demand in buildings. The study of the Building



Facades and Enclosures, Building for Sustainability. Figure 2
Deep energy conservation combined with passive conditioning including daylighting, natural ventilation, and passive solar can dramatically reduce energy consumption



Facades and Enclosures, Building for Sustainability. Figure 3
Critical facade elements to maximize access to the natural environment

Research Establishment of a portfolio of UK office buildings clearly illustrates the energy penalty of sealed, deep floor plan "prestige" buildings [7].

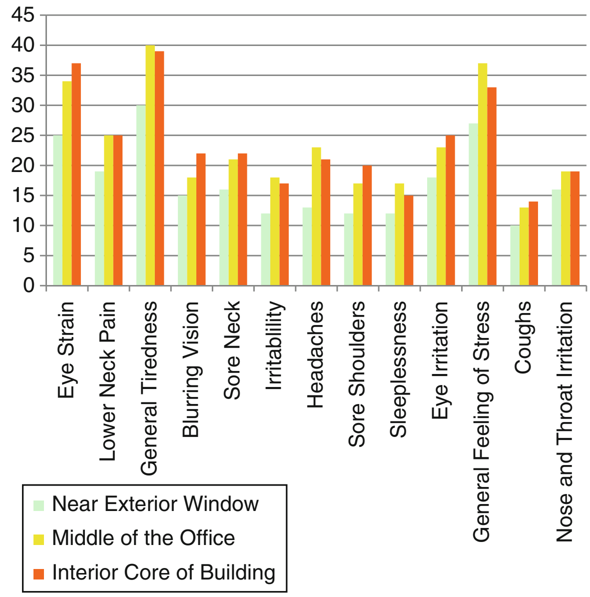
While there is significant debate about the importance of indoor daylight or sunshine for human health or performance, there seems to be a growing consensus that access to views is significant. Beginning with the seminal work of Ulrich [8], then Mendell [9], Heschong Mahone Group [10], and now Kellert [4], seated views of nature and proximity to windows are being linked to reduced length of stay after surgery, reduced sick building syndrome, increased performance at task, and overall improved emotional health.

In a 1990 survey of over 2,000 employees in two buildings at the US Department of Energy, Carnegie Mellon University's Center for Building Performance identified 10–20% lower sick building symptoms among employees with seated views of windows, controlling for rank [11]. Whether user perception of personal health is improved due to the light, the view, the perimeter conditioning systems, or an increased level of environmental control (blinds, HVAC controls) at the window is unclear. Regardless, there is a measurable benefit to ensuring that a workforce has fewer health symptoms across the board (Fig. 4).

Two case studies that frame the conclusion that views are a significant factor in health and productivity are captured below from the Carnegie Mellon Building Investment Decision Support Tool (BIDS™) [7, 8, 10]:

Window View of Nature = Health

In a 1984 observational field study at a Pennsylvania hospital, Ulrich identifies an 8.5% reduction in postoperative hospital stay (8.7 days vs. 7.96 days) for gall bladder surgery patients who had a view of a natural scene from their hospital room, as compared to those with a view of a brick wall. Patients with a view of a natural scene also received fewer negative evaluations from nurses and took fewer strong analgesics (Pennsylvania Hospital/Ulrich [8]).



Facades and Enclosures, Building for Sustainability. Figure 4
Window proximity correlates to a 5–25% reduction in health complaints among 2,000 workers in two US office buildings, controlled for rank [11]

Window View of Nature = Productivity

In a 2003 building case study of the Sacramento Municipal Utility District (SMUD) Call Center, Heschong et al. identify a 6–7% faster Average Handling Time (AHT) for employees with seated access to views through larger windows with vegetation content from their cubicles, as compared to employees with no view of the outdoors (SMUD/Heschong Mahone Group [10]).

These studies illustrate the value of windows with views for all occupied spaces, alongside effective design of window size and orientation, sight lines, and view content. The studies suggest that views of the outdoors should be with "biophilic" content – views of pedestrians and trees and community life – to critically maintain our sense of time and season. At the same time, it will be imperative for designers to ensure that requirements for glare control, heat gain and noise control, privacy and security are equally met—the definition of quality design (Fig. 5).

In pursuing design for sustainability, the challenge to designers is not only to connect indoor spaces with the outdoors visually, but to physically connect building occupants with nature – each site's unique climate and seasons, the textures, sounds, smells, and diversity of landscape and species. This not only suggests a shift away from mega-plexes and high-rise buildings toward open-air campus and village planning, but a commitment to operable windows, and distributed doors, terraces, and landscapes.

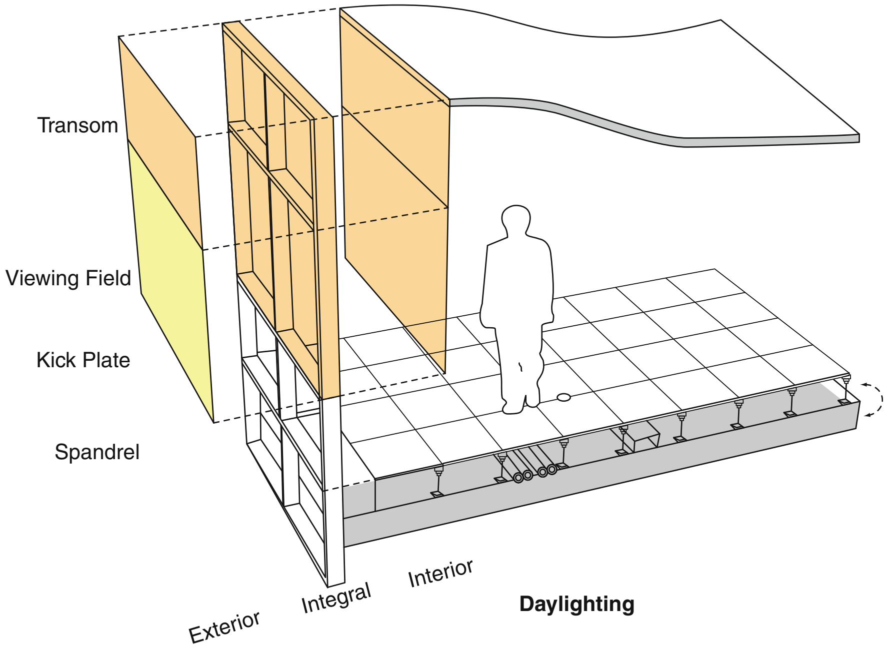
The physiological and psychological benefits of an ongoing connection to the locally unique and seasonally dynamic natural environment still need quantification. For example, studies in early childhood development reveal the academic and emotional benefits of natural playgrounds as opposed to hard-top play yards [12]. Sustainable buildings must incorporate physical access to outdoor spaces for a host of reasons, including physical exercise, exposure to sunshine and circadian rhythms, variations in thermal stimuli, and access to community (Fig. 6).

Facades that Ensure Daylighting as the Dominant Source for Both Task and Ambient Lighting

▸ *"A building with lights on during the daytime is not a sustainable building."*

Electric lighting is almost 25% of our primary energy use and over 35% of all electric energy use in the USA [13] – and much of that is during the daytime! Energy-efficient lamps, ballasts, and fixtures are obvious first steps for ensuring 30% lighting energy savings, and daylight responsive and occupancy responsive controls for these fixtures can reduce the next 20% (reference: see [14]). The giant leap, however, is achieved by buildings designed for daylighting as the *dominant* light source—environmentally "surfing" for 90% of the day without electric demand for lighting. This is more than rediscovering the design expertise of the nineteenth century. Good daylighting design demands effective integration of new glazing technologies, introducing light redirection and shading layers that enrich and regionalize architecture. Critically, buildings must be articulated, in finger or courtyard shapes, to ensure universal access to daylight.

Facades and Enclosures, Building for Sustainability. Figure 5
Designing window dimensions, orientations, and sight lines as well as adjacent landscaped spaces (with substantial storm water management benefits) are critical to ensuring access to views with "biophilic" content



Facades and Enclosures, Building for Sustainability. Figure 6
Critical facade elements to ensure daylighting as the dominant light source

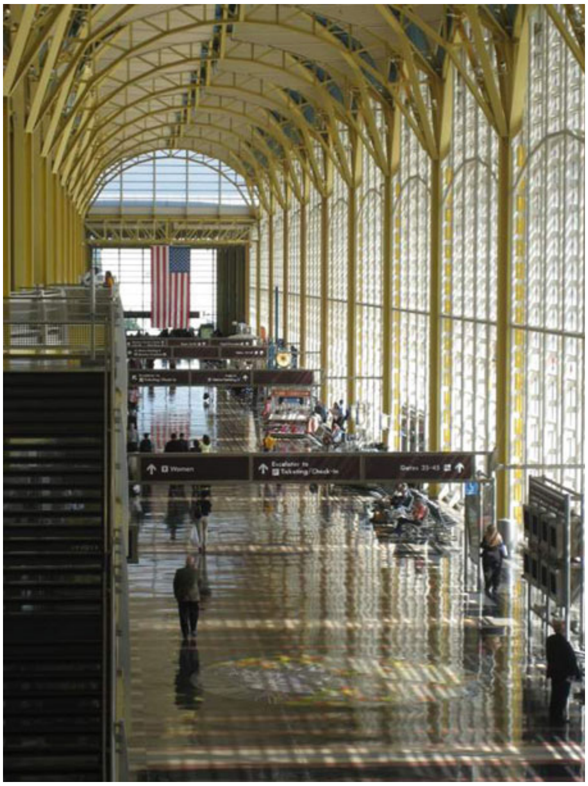
There are two main alternatives in the use of daylight in work environments. The first is the use of daylight for ambient lighting requirements of 200–300 lx and for spatial highlights. The second is the use of daylight as the dominant task lighting source at the work surface. This second alternative offers the greatest energy savings but also the greatest design challenge, since both the daylight "fixture" and the electric lighting interface need to be effectively designed. The daylight fixture – window, transom, or skylight – will need appropriate orientation, size, reflector-frame design and lens-blind design as well as the corresponding design of the room to ensure effective light distribution without glare.

There are a broad range of traditional and innovative technologies to be considered for effective daylighting of buildings to achieve both ambient and task lighting needs. New developments in glazing enable architects to specify high visual transmittance (short wave energy) while controlling solar transmittance and heat loss (long wave energy). Given innovations in glazing technology, it is possible to achieve high light transmittance over 50% while maintaining shading coefficients below 40% in cooling load–dominant climates, or above 60% in heating load–dominant climates.

However, sustainable design recognizes that not all shading should be solved with the glass selection, since this can rob spaces of daylight and solar heat where needed.

Each window must be designed as a lighting "fixture" in relation to space configuration and layout. If lighting engineers can design effective reflectors and diffusers for point and linear sources, they can design for planar sources as well. Transom glazing will be critical to effective distribution, combined with exterior, integral, or interior light redirection devices to ensure a more even distribution of daylight and to reduce glare from the window. If there is a shortage of window access, it should never be given to circulation aisles in a sustainable design (Fig. 7).

The rules for effective daylighting in offices, schools, and hospitals have long been established, relating to percent of aperture, ceiling height, room depth and color, as well as glare control and light redirection devices at the window. Today, high-performance



Facades and Enclosures, Building for Sustainability. Figure 7
Daylight is celebrated at Reagan National Airport, Washington DC

enclosures go even further, fully exploring the benefits of a layered facade. The design of layered facades enables seasonally and daily dynamic control of the light, heat, and ventilation energies available in the natural environment. All three layers should be designed together – external shading and light shelves to distribute daylight and reduce high sun angle glare; integral high visible transmittance glazing with climate responsive or dynamic shading coefficients; and internal light redirection blinds that sustain views while diminishing low sun angle glare. It is critical that the design of these layered facades be entirely regional in character, and suited to the function of the building, as they control light, glare, solar heat, heat loss/gain, even thermal mass. By displacing mechanical and electrical loads, these facades provide long-term energy savings. In retrofitting deep buildings for daylighting, the sustainable design community is exploring atria, light wells, light ducts, and light pipes. Bank of America in San Francisco cut an atrium into an overly deep building to bring daylight to all spaces. Innovations in light pipes, reflective ducts, and tracking/beaming heliostats all have potential for increasing daylight effectiveness and delight (Fig. 8).

At the same time, the daylighting "system" must give the appropriate information to the electric lighting interface so that it can offer the appropriate "infill" through continuous dimming control. Studies indicate that the selection, placement, and installation of the photo-sensor is critical, concluding that a ceiling-mounted photosensor shielded from direct window light will ensure the best correlation with daylight work-plane illuminance [15]. The net impact of daylighting and electric lighting integration is significant energy savings [16] and improved workplace satisfaction.

Emerging research is revealing that day-lit offices, classrooms, and hospitals may measurably contribute to greater health and performance at task. Light levels can be higher without energy penalty; full spectrum light offers rich color rendition and 3-dimensional modeling; circadian rhythms set by daylight variations throughout the day trigger melatonin production and sleep patterns; and views meet fundamental human needs.

Sustainable buildings are designed for daylight to meet all ambient and task requirements during the day. The investment in a layered facade for daylight effectiveness will simultaneously support natural ventilation, night ventilation, thermal load balancing, and passive solar heating – the full complement of regional opportunities for natural conditioning.

Daylight Lighting Control = Energy Savings

In a 1997 before and after building case study of the New York City federal building, the Electric Power Research Institute (EPRI) identifies 64% lighting energy savings and net HVAC energy savings of 0.07 kWh per square foot annually following the installation of an energy-efficient lighting system with daylight dimming and lumen maintenance controls (NYC Federal Building/ EPRI [16]).

Facades and Enclosures, Building for Sustainability. Figure 8
The central atrium and "sky gardens" at Commerzbank in Frankfurt bring daylight to all spaces and provide occupants with access to nature in a dense urban environment

Daylight Spectrum and Timing = Individual Productivity

In a 1997 controlled experiment, Boyce et al. identify a 1.6–12.8% improvement in night-shift workers' performance on short-term memory and logical reasoning tasks under large skylight-simulating fixtures with hidden fluorescent lamps, capable of providing fixed or variable illuminance from 200 lx to 2800 lx. Performance was enhanced by fixed high illuminance of 2800 lx and by steadily decreasing illuminance that simulated daylight from midday to dusk, as compared to fixed low illuminance of 250 lx or steadily increasing illuminance that simulated daylight from dawn to midday (Boyce et al. [17]).

Natural Ventilation = Health

In a 1991 multiple building study of 880 workers in eleven office buildings in the San Francisco bay area, Mendell identified 20–81% reductions in reported SBS symptoms for occupants of naturally ventilated buildings as compared to occupants of office buildings with air conditioning or mechanical ventilation (CA Healthy Building Study/ Mendell [9]).

Natural Ventilation = Health + Individual Productivity

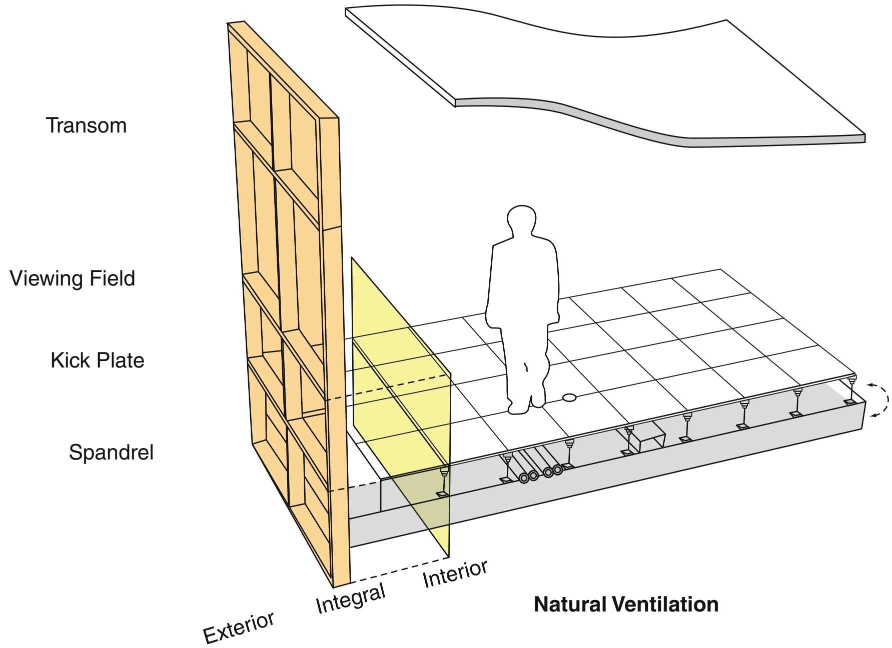
In a 2004 multiple building study of professional middle-aged women in France, Preziosi et al. identify a 57.1% reduction in absenteeism, a 16.7% reduction in medical services use (doctor visits), and a 34.8% reduction in hospital stays among subjects with natural ventilation in their workplace, as compared to those with air conditioning (Preziosi et al. [18]).

Facades that Ensure Natural Ventilation as the Dominant Fresh Air and Cooling Source Combined with Mixed-Mode HVAC Conditioning

► *"A sealed building is not a sustainable building."*

The use of *natural ventilation and natural cooling* with direct outside air for swing and winter seasons ensure affordable high levels of fresh air with the greatest energy efficiency (Fig. 9). International studies consistently link increases in outdoor air supply to both productivity and health gains in the workplace [9].

In addition, the substantial opportunity for "free cooling" through the use of outside air is significantly underestimated by calculations focused on only "comfort zone" natural ventilation. Natural cooling is possible whenever outside conditions are within or below the comfort zone both in the day and at night, as long



Facades and Enclosures, Building for Sustainability. Figure 9
Critical facade elements to ensure natural ventilation as the dominant fresh air and cooling source

as drafts can be effectively managed through mixing or heat recovery. The use of both passive (open windows) and active economizer cycles can save from 50% to 100% of the cooling demand in various regions of the USA, when including the benefits of nighttime cooling of the building's thermal mass [19].

Natural Ventilation = Individual Productivity + Energy Savings

In a 2002 multiple building study of 39 Australian office settings, Rowe identifies a 13.8% perceived productivity improvement, a 15% improvement in overall comfort, and 79% annual HVAC energy savings due to replacing a mechanical air-conditioning system with mixed-mode HVAC that supports both natural ventilation and air conditioning (Australian Offices/ Rowe [20]).

Design for effective natural ventilation and natural cooling of the building mass and its occupants requires multi-disciplinary expertise to ensure that building shape, orientation, atria/courtyards, chimneys, window types (awning, casement, double hung), sizes, and locations ensure effective cross and stack ventilation. Cross and stack ventilation demands that building form and space layout reflect prevailing wind directions and the potential for thermal and solar assist, often studied through wind model testing or computational fluid dynamic simulations. In climates with day-night temperature swings, night ventilation should be explored and building materials or storage selected to store cooler temperature, creating a thermal "flywheel" for the following day.

In many climates, *"mixed-mode" HVAC systems* are designed to support natural ventilation and to provide air conditioning and ventilation – when and where natural ventilation is inadequate. There are three types of mixed-mode HVAC systems [7]:

- Concurrent systems, which use natural ventilation and mechanical HVAC simultaneously. Occupants are free to open windows and the HVAC system provides supplemental ventilation, dehumidification, and cooling, while an advanced control system coordinates zone air supply rates with window positions.

- Changeover systems, where the building alternates between natural and mechanical mode on a seasonal or daily basis.
- Zoned systems, in which different conditioning strategies are used simultaneously in different zones of a building.

Concerns related to outdoor air pollution, pollen, and humidity can be effectively addressed with well-designed mixed-mode conditioning systems (Fig. 10). Natural ventilation in high-rise buildings demands both architectural and engineering innovations to manage both pressurization issues and stack effect. This has been accomplished through the design of stacked 6–8-story buildings such as the Commerzbank in Frankfurt, and through double envelope designs, where wind and pressure are moderated through intermediate facade spaces.

For both natural ventilation and mechanically assisted ventilation, it is critical to engineer *ventilation effectiveness*, ensuring adequate fresh air volumes through large apertures or economizers; accessible, large volume fresh air paths from air-intake locations to occupants, such as in displacement ventilation systems; multiple fresh air sources with operable windows, distributed air handlers or facade integrated HVAC; and adequate exhaust without recirculation or contamination of the air flow paths. Air intakes especially should be strategically located, not near loading docks with idling engines or on roof decks with standing water, but in non-polluted areas, without standing water or solar overheating. Indeed, air sources should be freshest where prevailing breezes travel through shaded, landscaped areas with some level of natural air purification and cooling.

To achieve effective natural ventilation with mixed-mode mechanical conditioning, the design team must work together to engineer and integrate the natural ventilation/natural cooling controls and the HVAC controls to maximize air quality, user control, passive conditioning, and energy efficiency. Given a growing body of research illustrated below, natural ventilation with mixed-mode conditioning should be the norm in all commercial buildings for human health and

Facades and Enclosures, Building for Sustainability. Figure 10
Operable windows at Commerzbank, a high-rise structure, provide natural conditioning for the occupants, linked with mechanical cooling in a hybrid system. The atrium at Institute for Forestry and Nature Research in Wageningen provides a protected space for natural ventilation in the offices while giving occupants a natural setting for meetings and relaxation

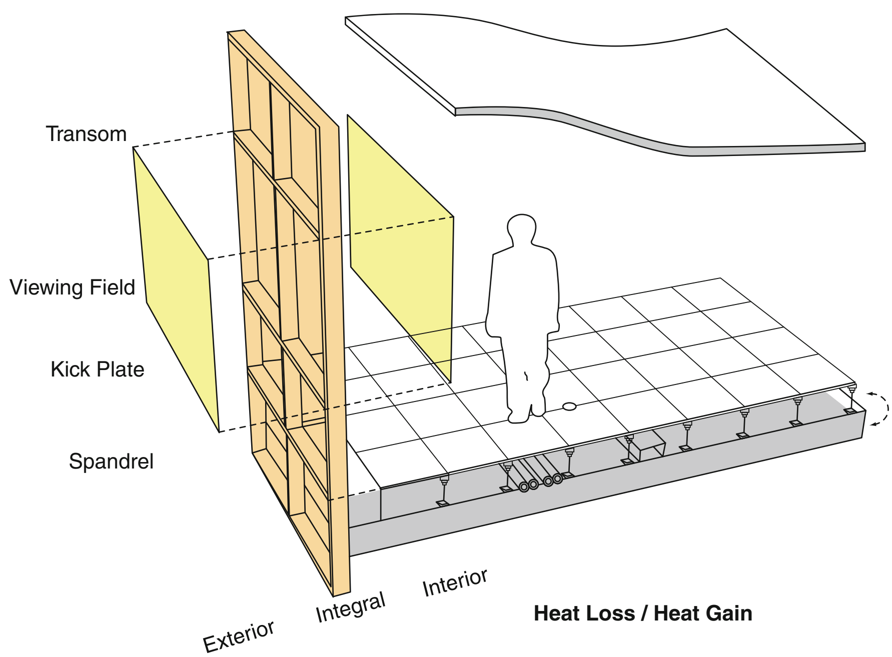
productivity, energy efficiency, and the viability of occupied spaces in the face of electricity shortages.

Facades that Minimize Enclosure Heat Loss/Heat Gain

One of the earliest decisions affecting the sustainability of buildings is the overall massing of the building and the *orientation of major facade and roof surfaces* (Fig. 11). While very harsh climates might benefit from minimum surface area to usable space enclosed, there are climate-specific arguments for increasing building enclosure for daylighting, natural ventilation, passive solar heating, and even the dissipation of excessive internal heat gains (see Load Balancing). These increased exposures must be strategic, however, avoiding solar overheating, cold air infiltration, and increased heat loss or heat gain. Serious re-evaluation of vast roof exposures and cantilevered floors is needed, minimizing excessive heat losses or heat gains unless they have corresponding benefits from natural conditioning. Even the location of the HVAC system will be significant, with rooftop and west facing cooling equipment measurably less efficient due to solar heat gains. Design goals should be set for building shape and orientation to ensure the best integration of passive conditioning while reducing environmental loads.

Architects make major decisions about the thermal performance of buildings through the specification of *window to wall ratios*. Sustainable designers weigh heat loss and heat gain against daylighting, natural ventilation, passive solar heating, and load balancing through the facade, alongside the spatial flexibility needed by dynamic organizations. Innovative building enclosures are designed to act like the human skin, dynamically supporting heat, air, and moisture dissipation for the health of the occupants in changing climates. The sustainable design community has rediscovered the opportunities for dynamic thermal performance of building enclosures, with high-resistance louvers, curtains, and dynamic layered facades changing heat transfer characteristics hour by hour, day to night, or season by season.

Needless to say, *the highest level of thermal resistance* to heat loss and heat gain is pursued for both the wall and window assemblies in sustainable buildings. Innovations in wall insulation have supported shifts from R5 per inch to R10 per inch – a doubling of



Facades and Enclosures, Building for Sustainability. Figure 11
Critical facade elements to minimize enclosure heat loss/heat gain

performance specifications. Window innovations also abound, with R2 double glazed assemblies replaced by R4, R8, and even R12 assemblies as a result of low-e, gas filled assemblies with innovative spacer and frame technologies, even while visible transmission is critically kept above 50%. At the same time, low solar heat gain coefficients (SHGC) of 0.35–0.50 can be achieved where needed to reduce overheating at the facade without loss of visual connection to the outside. At a very minimum, these three window variables – resistance to heat transfer (R), visible transmission (t_v), and solar heat gain coefficients (SHGC, solar transmission) – must be balanced in response to each climate and building type.

Facade Temperature Control = Individual Productivity

In a 2000 field case study of telecommunication office workers in Finland, Hannula et al. identify a 2.8% increase in measured productivity in north-facing offices with an average temperature of 23.6°C (range 21.9–27.8°C) as compared to south-facing offices with an average temperature of 25.2°C (range 22.8–28°C), supporting the need for improved heat gain control by orientation (Telecommunication Office/ Hannula et al. [21]).

Finally, sustainable enclosure design detailing ensures the *lowest level of thermal bridging* through walls, roofs, floors, and foundations. Structural and enclosure designers must work together to ensure the elimination or minimization of structural elements that connect indoor heated or cooled areas with the outdoors, including the facade, roof, floor, and foundation. Ideally the thermal "wrapper" is continuous and fully outside the structural frame, except at foundation connections that might indeed support ground source conditioning (see Thermal Load Balancing). Cantilevered balconies, overhangs, floors, and roof elements can contribute to significant heat loss, moisture and vapor migration, and condensation that lead to building degradation (see Enclosure Life). Not only the structural integration, but also product specification, enclosure detailing, and design for constructability are critical to the thermal performance of facades. There are numerous conditions where well-insulated facades, roofs, and foundations are compromised by penetrations that were not anticipated in the drawings (vents, tie rods, utility meters, etc.), or not adequately sequenced in construction to ensure the continuity of the thermal envelope.

One of the most exciting new developments in enclosure design is *green roofs and green walls*. Green roofs and their layers of waterproofing, insulation, soils, and vegetation have the potential to improve roof resistance to heat gain by 50% (NRC reference – see [22]), improve roof longevity by a factor of 2 [23], reduce storm water runoff by 50% [24], reduce air plane noise transmission, as well as reduce urban heat islands and air pollution [25, 26]. Green walls are also offering measurable gains by reducing solar heat gain, providing evaporative cooling, and creating seasonal qualities for our buildings (Fig. 12).

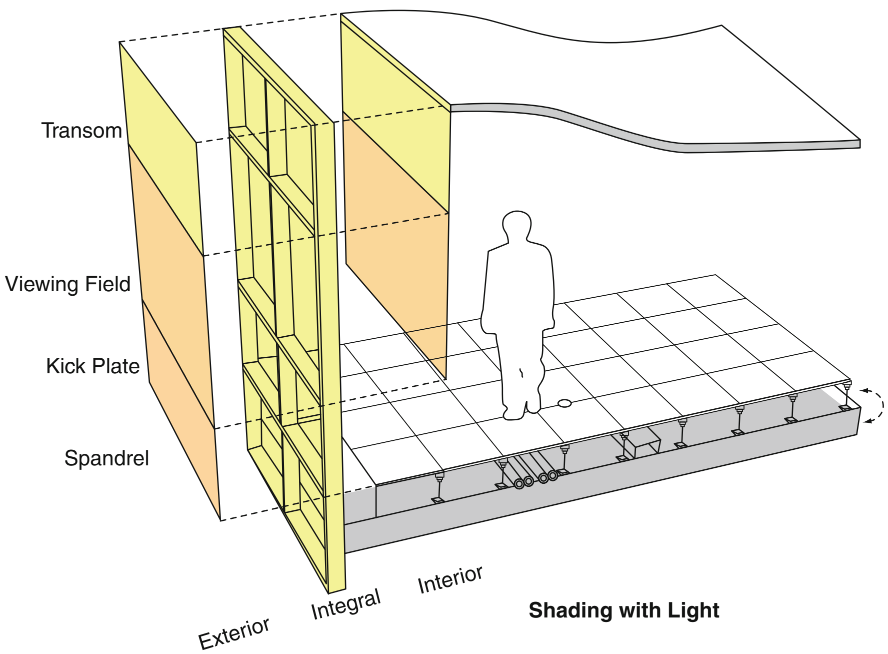
Green Walls + Double Skin Façade = Energy Savings

In a 2005 controlled lab experiment in the Netherlands, Stec et al. identify an 18% reduction in cooling system capacity requirements and a 19% reduction in cooling energy consumption for a double skin façade with plants in the cavity rather than blinds, due to a 20% reduction in temperature on the interior wall of the façade (Stec et al. [27]).

Facades that Integrate Climate-Responsive Shading and Glare Control

As with heat loss and heat gain, managing solar overheating and glare begins with the careful *sizing and location of windows* to ensure shade and light without glare (Fig. 13). East and West orientations are the most problematic, since sun angles are too low to effectively block with overhangs or open blinds. Skylights in horizontal roofs can also be problematic since they receive excessive solar heat in summer and significantly less winter energy (when solar energy is most beneficial). Window sizes and locations should be uniquely considered for each building face, as well as the detailing of internal and external controls.

Facades and Enclosures, Building for Sustainability. Figure 12
Green walls at Musee Branly reduce heat gain in summer



Facades and Enclosures, Building for Sustainability. Figure 13
Critical facade elements for climate-responsive shading and glare control

Integral shading devices, the selection of reflective or low transmission glazing, or the introduction of "frit" patterns to reduce solar transmission, are the most common strategies for shading and glare control. Unfortunately, low solar transmission glass will block useful gain in winter as well, and can also result in low daylight transmission. Many high reflectivity glass specifications inhibit daylighting, passive solar heating, and clear views of the landscape. However, new developments in glazing support high visible transmittance (daylight and view) with low solar transmittance (solar heat) for buildings in hot climates. Just as low-e glazing is becoming the norm for improved thermal resistance in glazing assemblies, this high-visible, low-solar glazing must become the norm for all buildings where cooling loads dominate on the perimeter.

A number of new glazing materials are emerging that support seasonally dynamic management of solar heat and light. Electrochromic, prismatic, and holographic glazing assemblies are in development that would enable the seasonal or hourly separation of light and heat spectrums, and the depth and color of the beamed light, so that building spaces can be naturally conditioned with the least amount of solar overheating or glare. The combination of these heat and light redirection devices with exterior and interior shading devices enable the appropriate percentages of the solar light and heat to be independently tapped.

Exterior shading devices, overhangs, light shelves, blinds, fins, and shades are the most effective means of reducing solar load while maintaining visual connection with the landscape. Clearly, the shading devices must be designed for each orientation, and for each site's climate and latitude. At least six types of exterior devices can be explored: an overhang/light shelf, recessed windows that act as an "egg-crate" shading device, dynamic shades or awnings, exterior blinds, exterior green walls, and a second dynamic facade (Fig. 14).

Just as a baseball cap allows a clear view of the action without glare in the eye, overhangs or light shelves can allow for views without glare and solar overheating. While an overhang provides shade from high sun angles, it could act as a light shelf and reflect sunlight deeper into the space when positioned below the upper (transom) portion of the window wall. Fully retractable exterior blinds can support both seasonal shading and daylighting goals, and enable views to be fully enjoyed during those hours when the sun is away from the facade. Awnings offer seasonally and daily adjustable shading on all orientations, full views when the summer sun has passed, and a colorful gaiety to the building. Landscape materials are re-emerging as effective shading for roofs, walls, windows, and terraces, self-regulating their density of shade to match the seasons, and offering potential to manage storm water as well.

Green Walls = Energy Savings

In a 2000 controlled experiment at Tanz Greenhouse at the University of Toronto and a follow-up computer simulation study, Bass and Baskaran identify a 23% reduction in cooling load and a 20% reduction in the fan energy use, for an 8% reduction in total annual energy consumption, when a green wall was used to shade an exterior surface of the building, as compared to an unshaded surface (Tanz Greenhouse/Bass and Baskaran [28]).

Facades and Enclosures, Building for Sustainability. Figure 14
Exterior shading devices at the Chesapeake Bay Foundation Headquarters are designed to account for different building orientations

The line of last defense, *interior shading devices* are somewhat less effective than exterior shading at minimizing solar load (heat gain from the sun), since the energy is able to enter the building before it can be reflected. While roll-down mesh shades provide a level of solar heat and glare control, inverted horizontal venetian blinds provide heat and glare control as well as daylight contribution for sustainable buildings. Research at the Lawrence Berkeley National Laboratories demonstrates that exterior operable shading devices, and even interior shading devices, are more cost effective and energy/resource effective than highly tinted (low visible transmission) glass *in all regions of the USA*, from Los Angeles to Chicago to Miami [29]. The selection of interior blinds should maximize light reflection, typically with a white or metallic color; maximize light distribution in the room, typically through inverted blinds and carefully shaped blinds that act as effective light shelves; and provide adjustable slat angles to maximize view potential while also maximizing work-plane illuminance [30] (Fig. 15).

If they are combined with exterior shades in a multi-layered facade, interior shades and blinds can be dedicated to light diffusion and glare management, with fabric/color selection designed to minimize brightness contrast between the window and its surroundings. Coupled with operable exterior shading devices, interior blinds could also be selected to *absorb* solar heat for perimeter heat gain in winter months. As innovations in phase change materials emerge, it is possible to imagine internal shutters or shades that absorb solar heat during the day, and then are reversed at night to radiate solar heat to the occupied space.

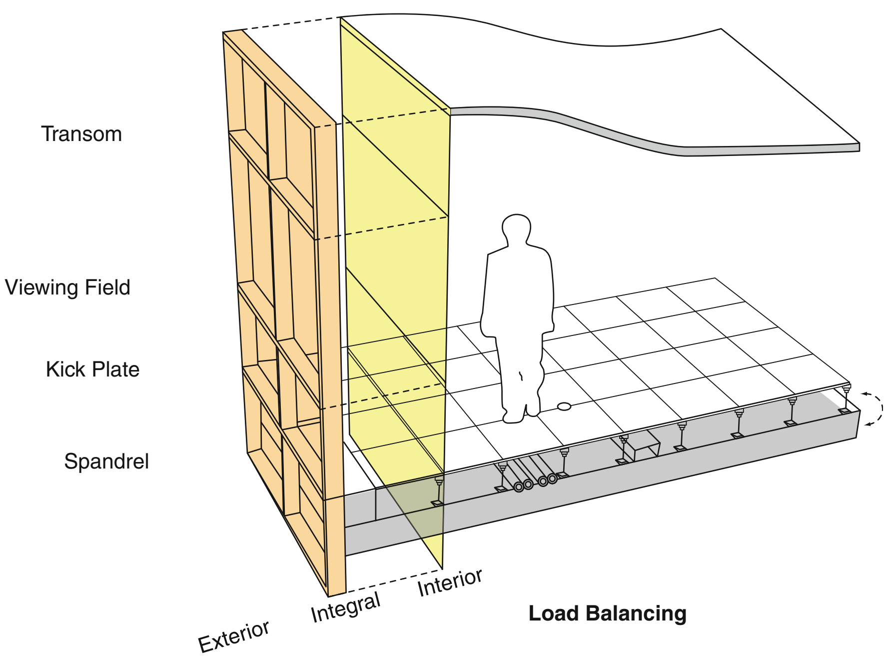
The most far reaching facade development in the past 10 years has been the development of *the double envelope*. When a second facade is introduced 1–3 m from the window wall, the intermediate space can be used to moderate the environment – heat, light, wind, noise, pollution, and other environmental stressors. These second facades house layers of shading, light redirection, air redirection, thermal load balancing, mechanical conditioning, and even dynamic levels of resistance to heat loss and gain. The research on the life cycle benefits of these innovations reveals significant variations in both costs and performance [31]. If double envelopes provide the greatest number of hours, days, and months without mechanical conditioning, they will be invaluable to carbon-neutral designers. The following section explores a number of enclosure solutions that use dimensioned "circulatory systems," such as double envelope designs, to reduce environmental loads in buildings (Fig. 16).

Facades that Engineer Load Balancing and Mean Radiant Temperature Control

To work toward healthier buildings with higher levels of local/individual comfort, it is imperative that the thermal imbalances, *mean radiant imbalances*, and conductive losses in buildings be addressed (Fig. 17).

Facades and Enclosures, Building for Sustainability. Figure 15
The dynamic light redirection louvers in the Robert L. Preger Intelligent Workplace can be configured to increase daylight levels in the interior spaces while reducing glare at the perimeter. Interior venetian blinds have engineered w-sections that manage low and high angle sun differently, reducing direct glare while maximizing view and daylighting

Facades and Enclosures, Building for Sustainability. Figure 16
Light shelves in the double envelope combined with external overhangs provide wonderful daylight and views for the new Cambridge public library



Facades and Enclosures, Building for Sustainability. Figure 17
Critical facade elements for load balancing and mean radiant temperature control

The engineering team is equally responsible with the architect for ensuring that the building enclosure detailing fully resolves thermal bridges and radiant imbalances.

As the internal heat gains in buildings have increased with office automation, the disparity in temperature conditions between facades and interior spaces has grown. Surprisingly, some designers have removed or reduced perimeter conditioning on the assumption that the interior loads will compensate for perimeter losses. This convective exchange will not be effective, however, without specifying super-insulated facade assemblies and/or deliberate load balancing by mechanically moving "core" heated air or water through the window wall.

Both air flow windows and water flow mullion systems enable excess heat from the building core – heat from occupancy, lights, and equipment – to be effectively dissipated through the facade. By taking return air through the "glass duct" of a triple glazed air-flow window, core cooling loads are dramatically reduced and perimeter heating is almost eliminated through *core-to-perimeter load balancing*. Water mullions (thermally broken from the outdoors) can also use "waste" heat from the core to minimize loads. In this system, waste heat from building cooling or power generating systems can be circulated through the facade to eliminate perimeter heating requirements and radiant imbalance, while allowing an increase in building periphery for views and light at every workstation. Indeed, the building facade could be seen as the natural dissipater of energy, a "circulatory system" resembling that of a healthy human – with appropriate surface to volume ratios. Given the constant increases in internal loads today, there is a real justification for increasing the periphery of buildings with the facade designed as an integral part of the mechanical system.

In addition to core and perimeter load differences, there are also significant load imbalances at different facade orientations, typically driven by solar load differentials (Fig. 18). One facade mechanical system of note is the use of double envelopes to provide *north-south-east-west load balancing* in climates where solar loads are significant and beneficial. The Occidental building in Niagara Falls is one of the earliest examples of a double envelope construction. When solar energy is received on the east, a natural convective loop of solar-heated air wraps the entire building. This continues throughout the day to eliminate simultaneous heating and cooling, to maximize passive solar

Facades and Enclosures, Building for Sustainability. Figure 18
In addition to radiant ceiling panels, radiant water mullions are integrated into the facade to balance temperatures year round in the Intelligent Workplace using water for energy-efficient load balancing

contributions to the heating load, and to ensure excellent mean radiant conditions. In summer, the double envelope is vented to the outside, and precautions are taken for fire protection. The Occidental building uses 70% less heating and cooling energy than a conventional office building in upstate New York [32].

A third strategy for reducing or eliminating the need for mechanical cooling is the use of *day-night load balancing* strategies. Night ventilation of a building's structural mass can successfully reduce or eliminate cooling loads in cooler climates, or climates with day-night temperature swings. Combined with the careful monitoring of dew point temperatures to avoid overcooling and condensation, nighttime cooling of a building's mass can provide adequate capacitance to absorb an entire day of internal gains. Thermal mass can be achieved through "heavy" or high-capacitance building walls and floors, or through the strategic introduction of phase change materials (PCM) to absorb and radiate heat as designed. A corollary to nighttime ventilation is the use of off-peak nighttime electricity to generate chilled water and ice or to chill PCMs for daytime cooling. This "ice storage" cooling strategy can be effectively bundled with nighttime ventilation of a building's thermal mass to absorb daytime overheating loads without peak electricity demands. Phase change materials also offer the potential for storing daytime solar heat for nighttime use, a strategy integrated into a number of PassivHaus projects [33].

For opaque enclosure surfaces, the value of high reflectivity surfaces in all overheated climates has led to a new era of "cool roof" design [34]. The combination of high reflectivity and night venting of enclosure mass in climates with day-night temperature swings has the greatest potential for natural comfort and low energy cooling [35].

Cool Roof = Energy Savings + Peak Demand Reduction + Extended Roof Life

In a 2002 multiple building controlled experiment in Florida, Parker et al. of the Florida Solar Energy Center identify 17.8–24.9% annual cooling energy savings and a 28.5–35.5% peak cooling load reduction from highly reflective white metal, white barrel tile, and white flat tile roofing; 9.5% annual cooling energy savings and a 12.9% peak cooling load reduction from terra cotta tile roofing; and 3.2% annual cooling energy savings and a 17.2% peak cooling load reduction from white asphalt shingles, as compared to dark asphalt shingles, on a single-family house (Florida Sustainable Energy Center/Parker et al. [35]).

The final load-balancing strategy for reducing heating and cooling loads in buildings is to take advantage of ground and aquifer temperatures through *ground-coupling*. Ten feet below ground, and in underground aquifers, the temperatures are surprisingly stable at year-round (inter-seasonal) averages of approximately 12–18°C (55–65°F). Given excellent temperatures for radiant, water and air-based cooling, high-performance building designers have tapped into this natural cooling potential through earth sheltered construction, large diameter "cool tubes," and aquifer or ground sourced chilled water loops that serve radiant, fan coil, or heat pump systems. Ground coupling significantly impacts foundation and flooring design, and might impact the facade "circulatory" systems as well (Fig. 19).

The benefits of active (mechanically integrated) load balancing to resolve mean radiant imbalances – from core to perimeter, from N/S to E/W, from day to night, and inter-seasonally through ground coupling – are many and are as follows: improved individual comfort, productivity, and health [36, 37]; reduced building material degradation from thermal differentials and condensation; significant energy conservation; and the potential to replace mechanical heating or cooling first costs and operating costs with high-performance building enclosures [38] (Fig. 20).

Radiant Cooling = Individual Productivity + Energy Savings

In a 1999 controlled field experiment and simulation study, Takehito et al. identify a measured 22% increase in speed and a 1.5% improvement in accuracy on simple tasks among women subjects and a simulated 10% HVAC energy savings in the Tokyo climate from a radiant ceiling cooling system as compared to conventional ceiling-based air conditioning (Imanari et al. [36]).

Facades and Enclosures, Building for Sustainability. Figure 19
"Cool tubes" beneath the greenhouses at Phipps Conservatory provide free cooling

Night Ventilation Cooling = Individual Productivity

In a 2003 meta-analysis study, Seppänen et al. identify a productivity increase equivalent to 0.39 h of work per day (4.9% for an 8-h workday) due to nighttime ventilation cooling of thermal mass, a very energy-efficient method of reducing daytime indoor temperatures by using nighttime air to cool a building's structure and furnishings (Seppanen et al. [37]).

Geothermal Heat Pump = Energy Savings + First Cost Savings

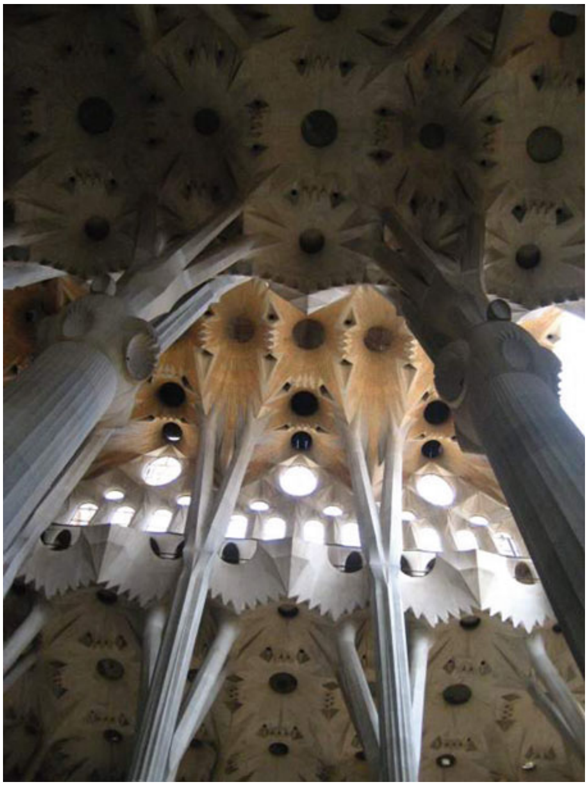
In a 1998 field study of Maxey Elementary School in Lincoln, Nebraska, Shonder et al. identify an average 47% reduction in annual HVAC energy use with a geothermal heat pump system as compared to the alternatives of VAV systems with air- or water-cooled chillers, as well as a first cost savings of $1.80/sf. Geothermal heat pump systems were found to have the lowest first cost, operational cost, and life cycle emissions of the three systems (Maxey Elementary School/Schonder et al. [38]).

Facades that Integrate Passive and Active Solar Heating, Cooling, and Power

The most direct use of solar energy in buildings is for *passive solar heating* (Fig. 21). The design of building enclosures to support direct gain through high solar transmission glass can effectively offset over 50% of the heat loss of buildings in many climates. Indeed, it is critical that glazing be carefully selected to ensure high solar transmission in cold climates to enable passive solar heating. In locations where direct gain would cause excessive daytime overheating or glare, the design of indirect gain passive solar facades – glazed mass walls or Trombe walls [39], water walls, or phase change walls – can strategically collect solar heat for nighttime heating. Recent developments in phase change materials that can be embedded in common construction or finish materials will help ensure that adequate solar heat storage exists to shift daytime solar gain to nighttime loads. Each of these solar heating strategies can be fully passive, utilizing no mechanical energy to collect, store, or distribute solar heat while providing potential health benefits to building occupants [40] (Fig. 22).

Sunlight = Health

In a 2005 building case study of Inha University Hospital in Korea, Choi identified a 41% reduction (3.2 days) in average length of stay among gynecology patients in brightly daylit rooms (317 lx average), as compared to those in dull rooms, in the spring, and an average 26% reduction (1.9 days) in average length of stay among surgery ward patients in bright rooms, as compared to those in dull rooms, in the fall. Across all seasons, the average daylight illuminance in bright rooms was 317 lx, compared to 190 lx in dull rooms (Inha University Hospital/ Choi [40]).

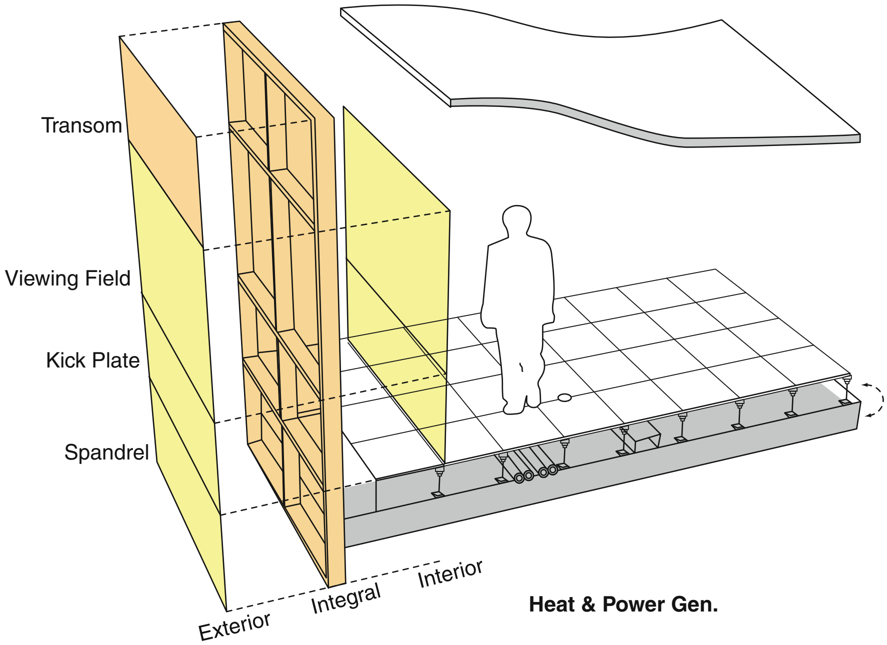


Facades and Enclosures, Building for Sustainability. Figure 20
Architecturally articulated thermal mass at Gaudi's Sagrada Familia minimizes daily temperature swings by night ventilation through architecturally expressive openings

The solar heat gained in building atria or double envelope facades can also be actively transferred to a range of storage media, from rock storage to phase change storage to underfloor air systems with thermal mass. *Active solar hot water* collectors integrated into building roofs or facades can also transfer solar heat to architectural or mechanical heat exchangers. The effective integration of solar heat gain with the ventilation air systems in buildings can significantly reduce heating loads while supporting greater ventilation rates for human health.

While solar thermal collectors can provide excellent hot water temperatures for heating, *concentrating solar thermal* collectors can generate the extreme high temperatures needed for cooling and power generation. Bundled with the latest in absorption chillers and steam power generators, a new generation of solar-evacuated tube and concentrating collectors are beginning to transform building enclosures to help meet the growing electrical demands in buildings for air conditioning (Fig. 23).

Finally, integrating *photovoltaic solar* (PV) elements into the building curtain wall or roof can generate on-site power for feeding into the grid or for immediate use in the building. For maximum efficiency, PV energy could be used directly as DC electricity (without transformer loses to AC) to meet the power demands of fans and air conditioners, plug loads, and dynamic facade elements – from operable windows to light shelves and shading devices. Recent thin film developments have significantly improved the performance of building integrated photovoltaics (BIPV), supporting a range of design choices regarding shape, orientation, transparency, and color. For windows, new PV glazing assemblies can provide effective shading, daylight distribution, and a competitive power source. The next generation of building windows may absorb solar energy in almost transparent coatings and carry the electricity to window mullions for transport to the grid. For roofs and walls, the early PV assemblies that were rigidly sandwiched behind glass have been replaced by newer flexible PV materials that can replace common building materials, with 3–10-year life-cycle justifications. The vast areas of roof and facade that absorb or reflect long hours of sunshine can be turned into an asset even in hot climates, with building integrated photovoltaics playing a major role in generating distributed power, eliminating the source and



Facades and Enclosures, Building for Sustainability. Figure 21
Critical facade elements for passive and active solar heating, cooling, and power

Facades and Enclosures, Building for Sustainability. Figure 22
Interior and exterior views of the south facade at Fraunhofer Institute in Freiburg illustrate the integration of active and passive solar strategies

distribution inefficiencies of conventional power production for greatly reduced carbon impacts.

Wind power generation can also be integrated with building facades and roofs. A new generation of micro-turbines may create the parapets of future buildings, and large wind farms may occupy the upper floors of skyscrapers, as proposed in early solutions for the World Trade Center by Battle Engineering [41].

Facades and Enclosures, Building for Sustainability. Figure 23
Concentrating solar thermal collectors on the roof of the Intelligent Workplace produce steam in the summer to power absorption chillers to cool the space

Photovoltaic System = Energy Savings

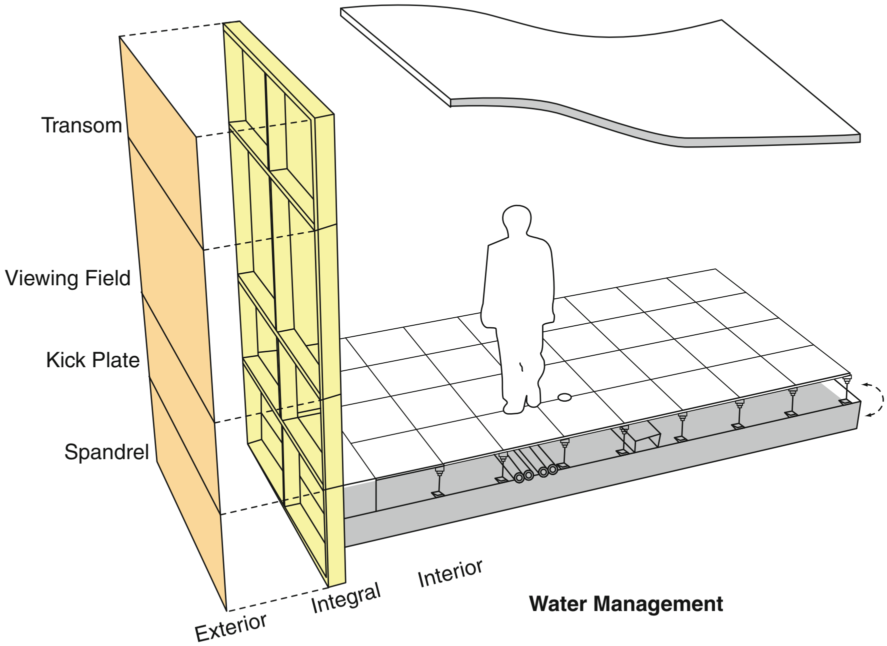
In a building case study of Bren Hall, a LEED Platinum-rated building at the University of California, Santa Barbara (UCSB), Aigner identified that the building's 47 kW rooftop photovoltaic system reduces purchased electricity consumption by 7–10% annually, at a first cost of $240,000, for an ROI of 5% (Bren Hall/ Aigner [42]).

Facades Designed to Manage Water

A fundamental role for high-performance building enclosures is the management of water. It is imperative that roofs and facades effectively *manage rainfall* through material selection and articulated detailing from top to bottom (Fig. 24). While gargoyles and expressive cornices that were once the solution to ensure heavy rains were shed away from the building, modern facades rely far too heavily on the caulked joint – often with poor results as the facades age (Fig. 25).

A lesser understood role for building facades is to *manage the vapor migration* that might lead to condensation on embedded surfaces that are below dew point temperature. This is typically achieved through the design of continuous vapor barriers on the "warm side of the facade" to stop the humidity from migrating into the wall. Detailing in design and construction supervision is critical, especially in complex climates where humidity and cold temperatures may both be from the inside or outside. In addition, moisture that is trapped in construction materials must be released naturally as well, typically through a vapor porous skin or vented air spaces [43]. *Rain screens* are an innovative solution to managing both rain and vapor migration. Rain screens introduce an uncaulked and vented second skin for the facade – typically of ceramic tile or metal or wood panels – that sheds the rain and utilizes the vented air space to eliminate moisture buildup.

As we embrace a greater set of sustainability challenges, building also need to collect rainwater today. As we face declining sources of fresh water, and increasing storm runoff challenges, the importance of designing building enclosures to *catch and store water* is of growing importance (Fig. 26).



Facades and Enclosures, Building for Sustainability. Figure 24
Critical facade elements to manage rainwater and moisture migration

Facades and Enclosures, Building for Sustainability. Figure 25
On the *left*, water sculpture by Herbert Dreisetl playfully manages storm water, enticing visitors to return in the rain to watch. On the *right*, rainwater capture provides acoustic and visual richness in the Dockside Green development by Joe Van Bellingham

Green Roof = Energy Savings + Peak Load Reduction + Storm Water Retention

In a 2002 building case study of the Chicago City Hall, the city of Chicago identified annual cooling energy savings of 0.02 kWh/square foot and annual heating energy savings of 0.02 therms/square foot, as well as a 70% reduction in storm water runoff, from installation of a 20,000 sf green roof (Chicago City Hall/ City of Chicago [44]).

Green Roof = Energy Savings + Storm Water Retention

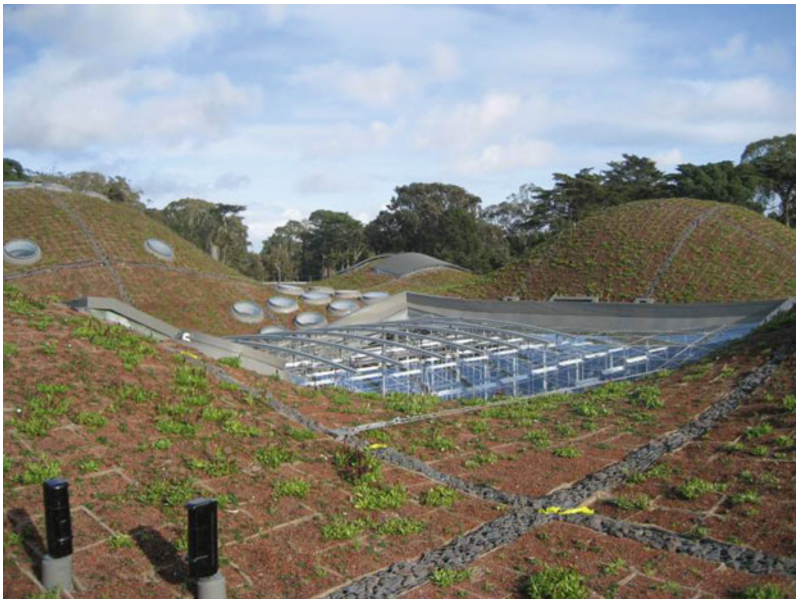
In a 2003 building case study of the 901 Cherry Offices of Gap, Inc. in San Bruno, CA, Green Roofs for Healthy Cities identify a 100% reduction in storm water runoff (7.54 gal/sf of roof area) and a simple payback of 11 years from energy cost savings alone (equivalent to 7% annual energy savings in a baseline building) due to installation of an extensive green roof (901 Cherry (GAP)/ Green Roofs for Healthy Cities [45]).

Facades that Maximize Enclosure Life

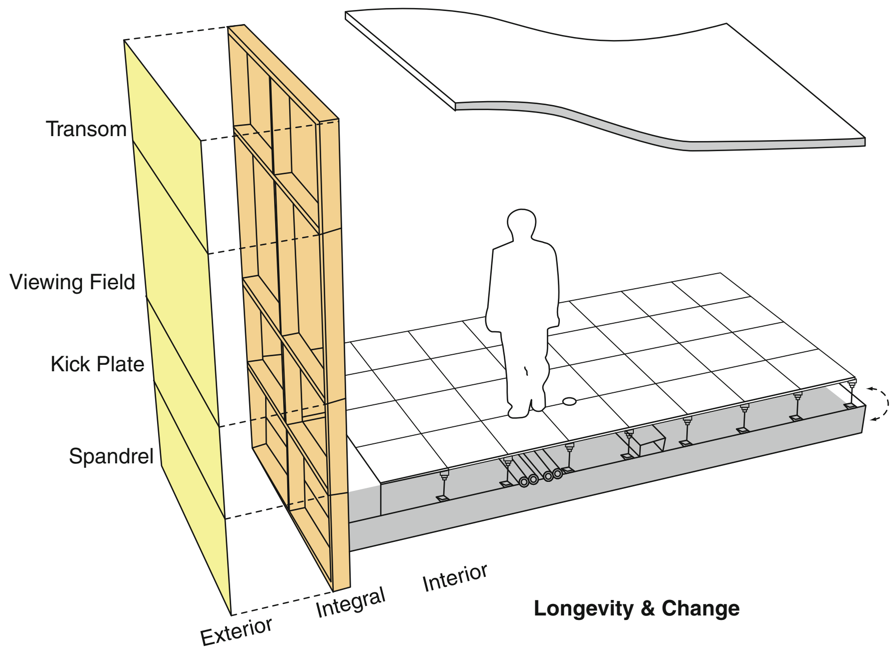
High-performance building enclosures will need to *use materials sustainably* (Fig. 27). Wherever possible, existing enclosures should be preserved to protect their "embodied" energy, or built of 100% recycled content materials. If virgin materials are used, their "chain of custody" should be known in relation to energy, carbon, rare materials, and toxicity. Toxic materials should be avoided in all assemblies, or designed for retrieval during disassembly.

Enclosure assemblies should be designed for their longevity, for natural *weathering and effective maintainability*. Most critically, enclosures should be designed and built for *cherish-ability*, the desire on the part of owners and the community to want to preserve the building rather than tear it down. This is typically ensured by the use of quality materials, assembled for longevity, and a high level of craftsmanship (Fig. 28).

Enclosure design must also address the needs for *human safety* in the face of manmade and natural disasters. This includes structural integrity in the face of earthquakes, hurricanes, and cyclones as well material integrity in the face of fires, floods, and blasts.



Facades and Enclosures, Building for Sustainability. Figure 26
Green roofs at the California Academy of Sciences capture storm water while providing a learning environment for landscape and habitats



Facades and Enclosures, Building for Sustainability. Figure 27
Critical facade elements to maximize enclosure life

Design for disaster protection should be about human safety not building protection, ensuring adequate egress and adequate safe harbors. Design for human safety must also ensure adequate access to water, breathing air, and light, even in the face of power outages – a redundancy that can be best achieved by sustainable facade design that fully incorporates natural conditioning.

At the same time, building enclosures need to be *designed for change* – for expansion or contraction, for changes in use or function. Change can be supported through building generosity, floor-to-floor heights, size of openings, and level of building articulation. Change can be supported by modularity, with a kit of parts that anticipates the evolution of scale and function over the life of the building. Change can also be accommodated by *design for disassembly*, by which the building and/or its enclosure can be relocated to a second or third life. All high-performance enclosure components, such as window and door assemblies, water management systems, and ornamental parapets, should be designed to be recovered as the "value-added" assemblies that they are well beyond the value of the raw materials (Fig. 29).

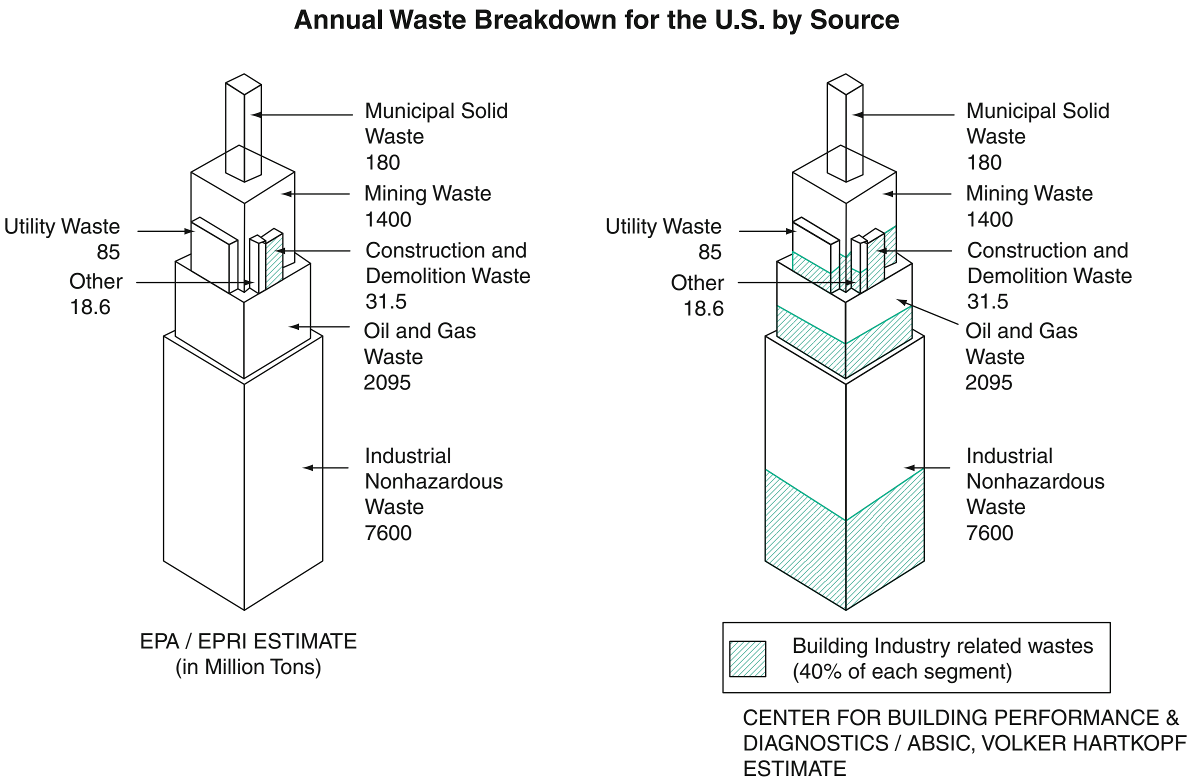
Construction Waste Management = Salvage/Waste Savings

In a 2004 building case study of the renovation of the Boston Scientific Company, Inc. office building, the Institutional Recycling Network identified a 32% reduction in disposal costs due to a comprehensive waste management process, compared to the cost of renovation with conventional landfill disposal of material waste. A site separation process allowed materials to be disposed of at lower costs than co-mingled materials and resulted in a 92% recycling rate by weight (Boston Scientific Company/ Institution Recycling Network [46]).

Construction Waste Management = Salvage/Waste Savings

In a 2000–2001 building case study of the demolition of the 133,000 square foot Hume Residence Hall on the campus of the University of Florida, Guy and Strong identify new revenues, reduced disposal costs, and cost avoidance from substitutions of reclaimed

Facades and Enclosures, Building for Sustainability. Figure 28
Historical structures were designed and built to last a lifetime



Facades and Enclosures, Building for Sustainability. Figure 29
Forty percent of the total waste stream can be attributed to the construction industry

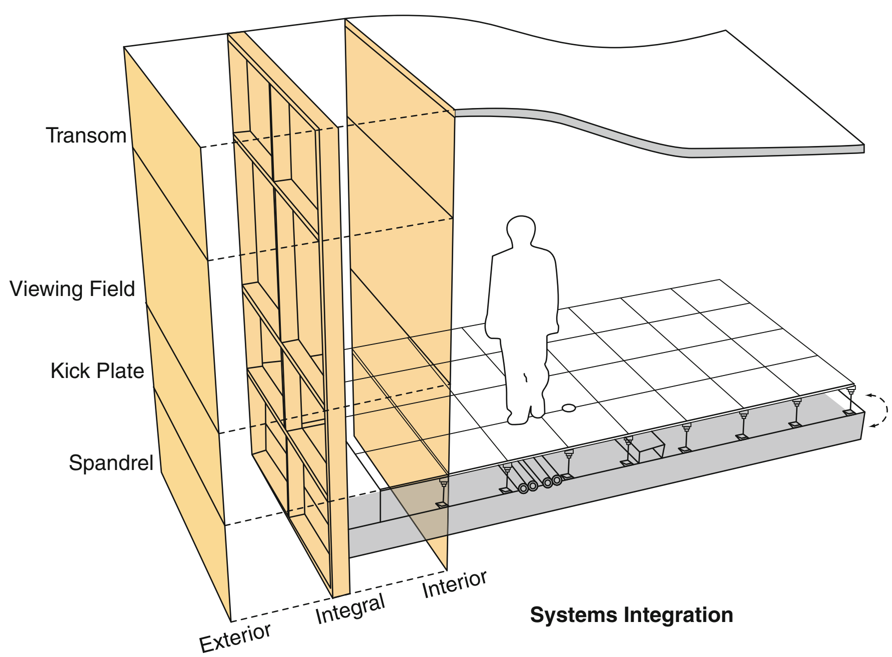
materials, achieved through a process of salvage and source separation of "debris" building materials. A comprehensive C&D debris management process resulted in a *net savings* of 4% compared to the cost of conventional demolition with extensive landfill disposal (University of Florida Hume Residence Hall/Guy and Strong [47]).

Future Directions: Facade Innovation Through Systems Integration

In times of limited resources and limited building budgets, some of the most innovative high-performance facades are achieved through systems integration (Fig. 30). At a very minimum, high-performance sustainable building facades will have to be collaboratively designed to:

- Integrate structure and enclosure to ensure heat loss/heat gain control, provide shading and glare control, and support daylighting.
- Integrate fire and enclosure to support load balancing innovations.
- Integrate HVAC and enclosure to support natural ventilation, load balancing, and passive and active solar energy utilization.
- Integrate interior systems and enclosure systems for access to nature, daylighting, natural ventilation, shade and glare control, and passive solar heating.
- Ensure design for enclosure life and design for change without waste.

When expert disciplines work collaboratively early in the design process, a range of innovations are generated – structural systems that offer shading and light redirection; enclosures that are integral with the mechanical duct or piping; fire egress that provides shade and access for maintenance; ornament that manages water; and expressions of function, culture, or ambition that serve a critical purpose for ensuring the highest level of indoor environmental quality and environmental sustainability. Sustainable building enclosures are the deliverables of integrated design teams and integrated building delivery processes that in turn are pivotal to achieving the highest level of health, productivity, energy, and environmental benefits (Fig. 31).



Facades and Enclosures, Building for Sustainability. Figure 30
Critical facade elements for innovation through systems integration

Whole Building = Energy Savings

In a 2000 building case study of BRE's Environmental office building in Garston, UK, Fisher et al. identify a 66% annual energy savings compared to a typical type III UK office building due to the use of thermal mass, natural ventilation, passive and low energy cooling, daylighting, high-performance electric lighting, and on-site power generation (BRE Environmental Building/Fisher et al. [48]).

Floor-Based Ventilation + Increased Outside Air = Health

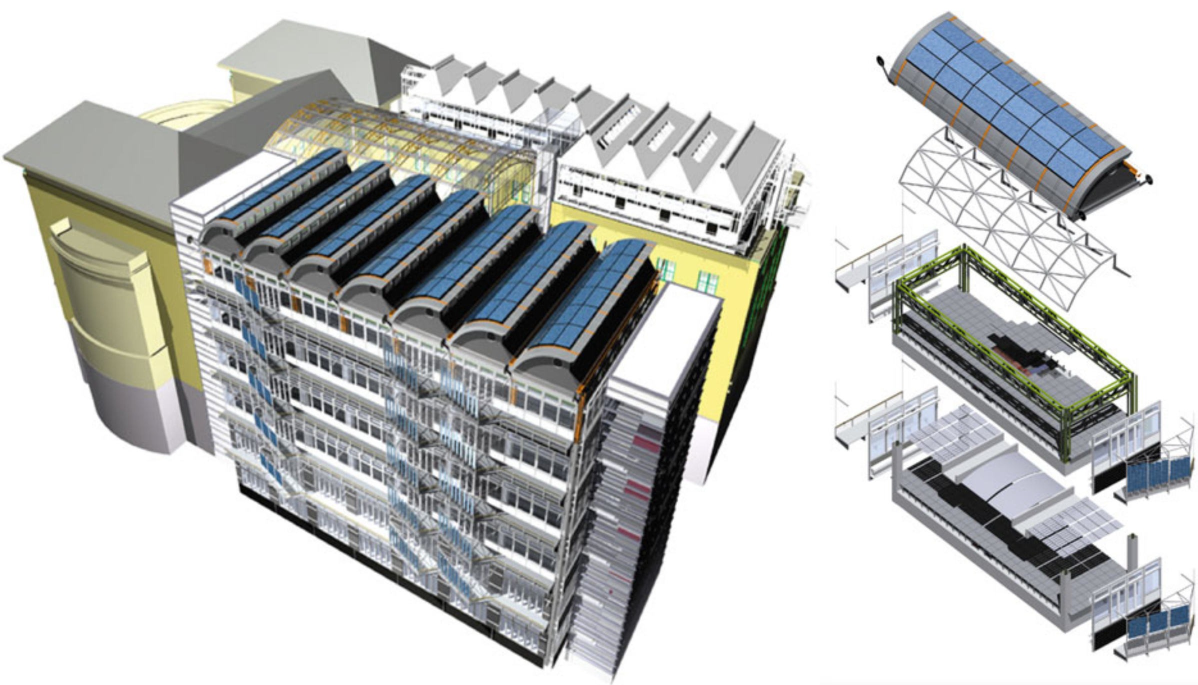
In a 2000 multiple building study of 39 schools in Sweden, Smedje and Norback identify a 69% reduction in the 2-year incidence of asthma among students in schools that received a new displacement ventilation system with increased fresh air supply rates and dedicated exhaust, as compared to students in schools that did not receive a new ventilation system (Elementary School/Smedje and Norback [49]).

High-Performance Building = Energy Savings + Rent Premium

In a 2004 building case study of the Phillips Eco-Enterprise Center in Minneapolis, Brinkema identifies \$0.31/sf energy savings and a 5–10% lease premium for the building owner (a financial gain of \$0.62/sf) due to high-performance building design that incorporates passive solar and geothermal heating and cooling, daylighting and high efficiency electric lighting, salvaged building materials, nontoxic paints and finishes and landscaping with native plants (Philips Eco-Enterprise Center/ Brinkema [50]).

High-Performance Building = Energy Savings + Individual Productivity

In a 1992 building case study of ING Bank in Amsterdam, Bill Browning of Rocky Mountain Institute identifies a 92% reduction in primary energy consumption and a 15% reduction in employee absenteeism compared



Facades and Enclosures, Building for Sustainability. Figure 31
The proposed "Building As Power Plant" at Carnegie Mellon University attempts to integrate all building systems, assemblies, and components to export unneeded renewable energy while providing optimum comfort for the occupants

to the bank's former headquarters, due to high-performance design strategies including daylight, a narrow floor plan that allows landscaped views for every occupant, passive solar conditioning, co-generation, and the use of heat exchangers (ING Bank/ Browning [51]).

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Geothermal Conditioning: Critical Sources for Sustainability

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Article of Outline

Glossary

Closed loop system A continuous, sealed, underground or submerged heat exchanger through which a heat transfer fluid passes to and returns from building conditioning equipment.

Geothermal direct use Use of thermal energy in the earth or earth-coupled fluid as a heat source and heat transfer reservoir for heating or cooling, without further conversion such as electric power generation.

Geothermal heat pump A conditioning device that uses the ground or ground-coupled fluid as the heat source and heat sink in the heat pump's process of extracting heat from a low-temperature source and transferring it to sink at a higher temperature by adding the work of a refrigerant, usually with a vapor compression-expansion cycle.

Low-Exergy System Heating and/or cooling system that uses energy at a temperature close to room temperature for efficient utilization of low-grade energy sources.

Open Loop System A system designed to use groundwater or surface water for the purpose of extracting or rejecting heat for building conditioning.

Underground Thermal Energy Storage (UTES) A subsurface system for storing heat and/or cold using groundwater and/or the ground in natural or constructed media.

Definition of the Subject

Geothermal conditioning is use of the earth's thermal energy and storage capacity for heating, cooling, and ventilation. These types of conditioning strategies can transfer heat to the indoor environment using the ground, groundwater, or surface water – resources that are abundant and ubiquitous – to satisfy some or all of the heating load. They can also capitalize on the heat capacity and thermal inertia of the earth and its waters by transferring excess heat from indoors to outdoors, providing cooling with substantially reduced energy consumption from conventional cooling and negligible thermal impact on the outdoor environment.

Geothermal conditioning, like solar conditioning, includes passive and active strategies. Both have a long history. Passive earth sheltering has been used by plant and animal species throughout time. Active geothermal conditioning as defined here for heating, cooling, and ventilation was not broadly tracked until 1995 when geothermal heat pumps were added to global reports of geothermal direct use installations [1]. However, frequently cited early examples are the district heating system installed in Boise, Idaho (USA) in 1892 to heat 400 homes [2] and a residential geothermal steam heat system in Tuscany, Italy, introduced between 1910 and 1940 [3]. In present times, the Paleiskwartier district geothermal system in ‘s Hertogenbosch, the Netherlands, includes a large pond and aquifer thermal energy storage (ATES) coupled with heat pumps to condition a mixed-use development of 1,200 housing units and more than 135,000 m^2 of office space, retail, and entertainment [4].

Accessible geothermal energy includes ground temperatures in excess of 150°C, hot enough to generate electricity and higher than temperatures that can be used directly for building conditioning. In such situations, building conditioning can be linked to geothermal power production through energy cascades, but

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the cost and complexity of power production processes substantially exceed those for building conditioning alone. In addition, access to geothermal resources that support electricity generation is far more limited. For those reasons, this entry will focus on direct use geothermal conditioning. References that address geothermal power production and geothermal energy cascades are provided in the Future Directions and Books and Reviews sections.

Introduction

In 1973, an Icelandic engineer, Baldur Lindal, listed current and potential uses of geothermal energy for conditioning and industrial processes and their temperature requirements. That list became known as the Lindal diagram, shown in Fig. 1 with conditioning processes highlighted. Since that time, substantial improvements in the availability and use of insulation products have allowed well-designed building

Temperature (C)	Application	
200		
190		
180	Evaporation of highly concentrated solutions, Refrigeration by ammonia absorption, Digestion in paper pulp (Kraft)	
170	Heavy water via hydrogen-sulfide process Drying of diatomaceous earth	Conventional power production
160	Drying of fish meal Drying of lumber	
150	Alumina via Bayer's process	
140	Drying farm products at high rates Canning of food	
130	Evaporation in sugar refining. Extraction of salts by evaporation and crystallization, Fresh water by distillation	
120	Most multi-effect evaporation. Concentration of saline solutions.	
110	Drying and curing of light aggregate cement slabs	
100	Drying of organic materials, seaweeds, grass, vegetables, etc. Washing and drying of wool	
90	Drying of stock fish Intense de-icing operations	
80	Space heating (buildings and greenhouses)	
70	Refrigeration (low temperature limit)	
60	Animal husbandry Greenhouses by combined space and hotbed heating	
50	Mushroom growing Baleonology	
40	Soil warming	
30	Swimming pools, biodegradation, fermentations, Warm water for year-round mining in cold climates, De-icing	
20	Hatching of fish. Fish farming	
10		
5		
0		

Geothermal Conditioning: Critical Sources for Sustainability. Figure 1
Original Lindal diagram: geothermal energy uses

°C	Low Range of Conditioning Technology/Process
100	
90	
80	Cogeneration supply for district heating system
70	
	Conventional boiler supply temperature
60	
50	Fan coil heating water supply, Forced air furnace, Radiator water supply
40	
30	Floor heating, Ceiling panel heating, Wall panel heating
20	
10	Ceiling panel cooling water supply Sewer water supply temperature
0	District cooling Fan coil cooling water supply, Earth sheltering, Earth tube supply air Extended range heat pump entering water temperature: cooling
–10	Extended range heat pump entering water temperature: heating

Geothermal Conditioning: Critical Sources for Sustainability. Figure 2
Low-temperature/low-exergy conditioning

enclosures to manage an increasing portion of the conditioning loads. When that occurs, heating and cooling can be provided at temperatures much closer to the human comfort range, no longer needing to overcome extreme heat loss or gain at the perimeter. Sustainably designed buildings can satisfy occupant comfort requirements with smaller mechanical equipment that operates at lower supply temperatures, supporting low-exergy systems (see Fig. 2). This puts building conditioning squarely in the geothermal "sweet spot," a temperature range available to almost every building in contact with the earth. Increased use of geothermal conditioning strategies will significantly lower conventional energy consumption, peak demand, and the corresponding carbon emissions, if done with understanding of these systems and their interaction with the environment.

This entry begins with a discussion of the earth's thermal energy and its ability to supply and store heat. The range of geothermal conditioning approaches are then described and illustrated with pertinent examples. Available data on global use of geothermal conditioning are presented and likely future developments in the design and application of geothermal conditioning technology are discussed. Finally, printed and electronic sources of additional information about geothermal conditioning are enumerated.

The Earth's Thermal Energy Sources and Ground Temperature Distribution

The European Union succinctly defines geothermal energy as *the energy stored in the form of heat beneath the surface of the solid earth* (RES Directive 2009/28/EC). Nothing in that definition, however, suggests the dynamic nature of the heat storage processes. Some of the short wave solar radiation incident on the surface is absorbed and conducted into soil and rock.

Precipitation, either rain or snow melt that percolates into the subsurface, can transport this thermal energy substantially farther into underlying aquifers and the soil and rock surrounding them. Thermal energy is also created within the earth through the decay of radioactive isotopes such as U^{238} and Th^{232} in granite and basalt in the earth's crust, and through earthquake friction and the formation of new crust. These types of heat energy, in addition to thermal energy stored when the earth was formed, are transferred via conduction and convection from the interior of the earth to its surface. At the surface, long wave radiation and convective flow to the atmosphere balance the thermal energy inputs. The earth's total heat energy content is estimated to be 12–24 10^{30} J [5].

Within the earth's internal energy reservoir, temperatures are estimated to reach 5,000°C (see Table 1). However, because the earth has been drilled only to a depth of 12,262 km, less than 1% of the earth's diameter [6], and the present limit of economic drilling is approximately 4 km, the practical maximum temperature of geothermal energy is now <1,000°C. Constraining that range to temperatures effective for direct use geothermal conditioning, the range is approximately 4–150°C. An even smaller range, roughly 4–27°C, is sufficient for energy-effective building conditioning (see Fig. 2). In many areas around the world, solar radiation supplies the thermal energy for most of that temperature range in the top 20 m of the earth's surface.

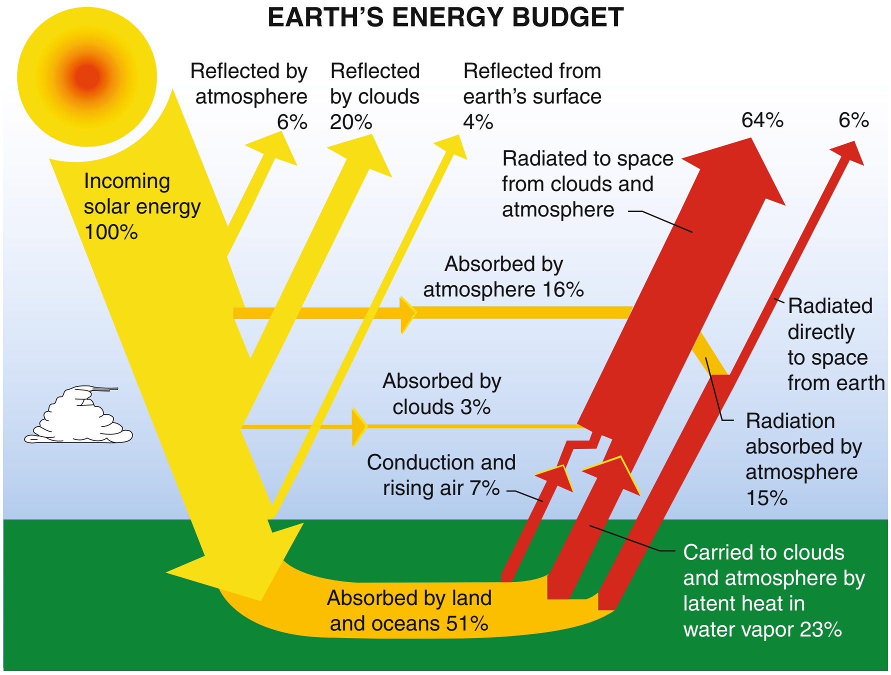
Solar Energy Input: When the sun strikes the earth's surface, the radiation must be reflected from the surface, absorbed by the surface, or transmitted through the surface to material below. For most ground surfaces, the radiation is either reflected or absorbed; some transmission occurs through snow and ice. In approximate percentages, of the total solar radiation that enters the earth's atmosphere, roughly 55% reaches the earth's surface where 4% is immediately reflected to the atmosphere and 51% is absorbed (see Fig. 3).

The thermal impact of that absorbed radiation can be affected by dynamic processes such as wind and rain, but the static properties of the surface soil, water, and underlying rock are typically used to calculate how solar radiation affects ground temperature. The thermal *conductivity* of a material, expressed as k or λ in units of W/m/K, indicates how readily heat is transferred within a material by rapidly colliding molecules. It is an important mode of heat transfer in solids although most soils and rock are relatively poor conductors. The *specific heat* of a material, expressed as c_p in units of J/kg/K, indicates how much thermal energy a material can absorb for a given change in temperature. A material's specific heat and its *density* (ρ) in kg/m^3 determine its *volumetric heat capacity*, expressed as ρc in units of MJ/m^3/K. Volumetric heat capacity is the specific heat per unit volume and indicates the ability of a substance to store energy without undergoing a phase change. Soil and rock have a very high volumetric heat capacity relative to air and their ability to store heat creates a useful thermal lag. *Thermal diffusivity*, which indicates how quickly a material adjusts to the temperature of its surroundings, is calculated by dividing conductivity by volumetric heat capacity. Thermal diffusivity is expressed as κ in units of m^2/s. A highly conductive material with low volumetric heat capacity will have high thermal diffusivity and readily adjust its temperature, whereas a material with similar conductivity but higher volumetric heat capacity will adjust more slowly. In contrast to high thermal diffusivity, a material with high *thermal inertia* will store heat and give it off slowly, resisting diurnal and seasonal temperature changes. Thermal inertia is the square root of the thermal conductivity, density, and specific heat capacity expressed as I with units of $J\ m^{-2}\ K^{-1}\ s^{-1/2}$. Table 2 summarizes these properties and Table 3 shows representative values for air, water, soil, and rock.

Table 3 highlights the benefits of ground- or groundwater-based conditioning compared to air-based strategies. The thermal inertia of water, soil, and rock is high. Surface temperature fluctuations

Geothermal Conditioning: Critical Sources for Sustainability. Table 1 Earth temperature profile [7]

Earth layer	Depth (km)	Temperature (°C)
Near-surface solar zone	0–0.02	Similar to mean annual air temperature
Earth's crust	0–30	Up to 1,000
Earth's mantle	Up to 3,000	1,000–3,000
Earth's core	Up to 6,370	3,000–5,000



Geothermal Conditioning: Critical Sources for Sustainability. Figure 3
Absorbed and reflected solar radiation

Geothermal Conditioning: Critical Sources for Sustainability. Table 2 Key soil and rock properties for thermal performance

Property	Common symbol	Units	
Density	ρ	kg/m	
Specific heat capacity	c_p	J/kg K	
Thermal conductivity	*k* or λ	W/m K	
Volumetric heat capacity	ρc	MJ/m^3 K	Specific heat * density
Thermal diffusivity	α or κ	m^2/s	Conductivity/volumetric heat capacity
Thermal inertia	I	$J\ m^{-2}\ K^{-1}\ s^{-½}$	√ density * specific heat * conductivity

diminish with depth and the time lag between the surface temperature and the ground temperature increases. Daily fluctuations are dampened within 30 cm of the surface [8]. Annually, surface temperature fluctuations reflect monthly solar cycles and attenuate with increased depth, and the time lag between the surface temperature and ground temperature is more extended with depth on an annual basis. At the depth of *zero annual range* [9] or *the neutral zone* [10], the atmosphere and soil are presumed to achieve long-term thermal equilibrium. Here, no seasonal temperature fluctuations occur and the ground temperature should reflect the long-term average annual air temperature for that particular location. Under these circumstances, the ground temperature is warmer in winter and cooler in summer than the air temperature, which means that the ground can provide heat in winter and absorb excess heat in summer.

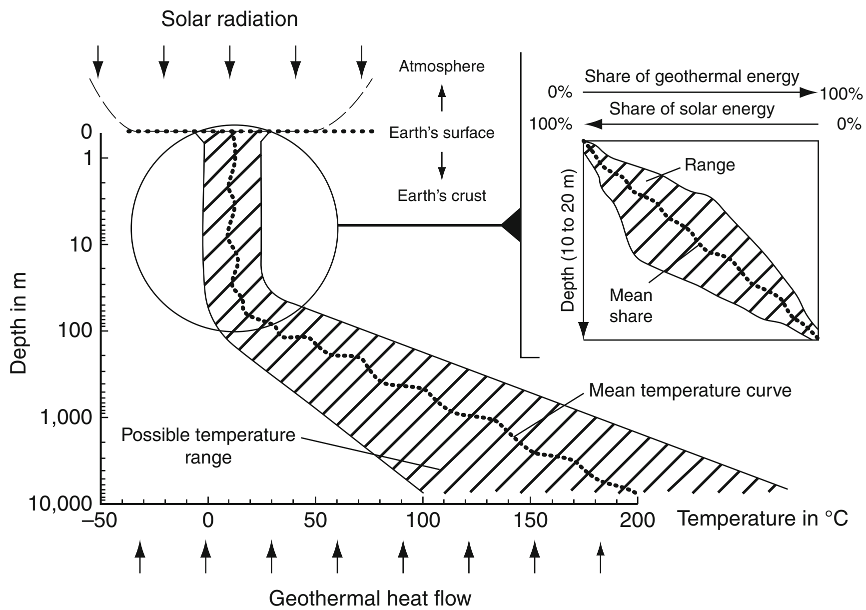
Geothermal Conditioning: Critical Sources for Sustainability. Table 3 Surface and ground properties affecting subsurface temperature change

Material	Density (ρ) in kg/m^3	Specific heat capacity (c_p) in J/kg K	Volumetric heat capacity (ρc) in 10^{-6} J/m^3 K	Thermal conductivity (*k*) in W/m K	Thermal diffusivity (κ) in 10^{-6} m^2/s	Thermal inertia (I) in J m^{-2} K^{-1} s$^{-½}$.
Air (STP)	1.29	1,005	0.0012	0.02	15.43	5.09
Water	1,000	4,186	4.19	0.60	0.14	1,585
Sandy soil (dry)	1,600	800	1.28	0.30	0.23	620
Sandy soil (saturated)	2,000	1,480	2.96	2.20	0.74	2,552
Clay soil (dry)	1,600	890	1.42	0.26	0.18	192
Clay soil (saturated)	2,000	1,550	3.10	0.58	0.19	1,341
Rock (basalt)	2,600	800	2.08	2.50	1.20	2,280

Table 3 also shows the impact of subsurface moisture. Saturated soil has substantially greater specific heat, volumetric heat capacity and thermal inertia than dry soil, making it a far better and more stable heat source and sink. If soil moisture varies with precipitation, the ground's thermal properties will reflect that variation. Alternatively, if soil moisture can be controlled to some extent, it may be possible to improve ground performance for geothermal conditioning.

The depth at which the neutral zone is said to occur varies within the literature (14–20 m) [9, 10] and is typically calculated, not measured. This is not surprising since determining the density, conductivity, and specific heat of heterogeneous soil and rock layers is difficult. In fact, the ASHRAE *Handbook of HVAC Applications* acknowledges that long-term field-monitored data are a major missing component in the effort to improve calculations for geothermal system design (greater detail about calculations for geothermal system design is provided by Kavanaugh and Rafferty) [11]. More important than the specific depth of the neutral zone is its occurrence in the ground temperature profile. Within a few meters from the earth's surface, a zone in which building foundations exist, the ground temperature reaches or approximates long-term thermal equilibrium with the atmosphere due to incident solar radiation. Effective integration of the ground's low-temperature heat supply and heat storage capacity can substantially reduce consumption of nonrenewable energy for building conditioning.

Interior Energy Input: Beyond the neutral zone, the temperature typically rises with depth, following what is called the geothermal gradient, shown in Fig. 4 as a broken line descending from the surface. The temperature rise along the geothermal gradient reflects heat flow from the earth's interior via conduction through solid rock and convection within geothermal fluids. Of the sources of heat energy within the earth, *radiogenic heat*, from the decay of radioactive isotopes, contributes the greatest share, annually estimated as 8.6×10^{20} J [13]. The geothermal gradient can vary substantially by locale and region. Recent research suggests that the gradient can be lowered or reversed, at least to 250 m depth, with increased energy input at the surface. Ongoing monitoring of well temperatures by Majorowicz et al. shows that rising surface air temperatures are increasing the amount of thermal energy stored in the shallow geothermal environment in some locations. Their analysis of temperature changes down to 250 m shows that the near-surface heat gain is also creating a null or negative thermal gradient. As a result, drilling below 50 m depth in these locations offers little thermal benefit for heating applications [14].



Geothermal Conditioning: Critical Sources for Sustainability. Figure 4
Ground thermal flows and temperature profile [12]

Their findings also suggest that the ground's near-surface thermal storage (heat sink) capacity may diminish with rising air temperatures.

Globally, the average geothermal gradient ranges from 30 to 60 K/km, but the gradient may be a little as 10 K/km in older crustal areas or as high as 200 K/km in tectonically active areas such as Iceland. The most tectonically active country on earth, Iceland has more than 200 volcanoes. Nearby ground temperatures exceed 200°C at 1 km depth and outside the volcanically active zone, the geothermal gradient is still quite high at 150°C/km. In 2008, 62% of Iceland's primary energy and 24.5% of its electricity came from its geothermal resources [15].

Geothermal Conditioning Principles and Approaches

An essential principle in sustainable building design is to create a building enclosure that manages as much of the heating, cooling, and ventilation loads as possible [see "High Performance Building Facades: Enclosures for Sustainability," V. Hartkopf, A. Aziz and V. Loftness in this volume]. With a high-performance enclosure, the size of the mechanical equipment and its related energy consumption and carbon emissions are reduced. In addition, sustainable building conditioning employs the following general strategies [16].

- Use water as an energy carrier since it carries 3,000× the energy that air carries in an equivalent volume.
- Use low-exergy systems, independently or as part of an energy cascade, to match the energy content of the supply more closely with the need.
- Use distributed rather than central systems, that is, multiple small units distributed throughout the building with commensurate controls rather than a single large central unit to cut transmission losses and to deliver thermal comfort close to building occupants.
- Zone the system to allow equipment to operate at full load efficiency and only when needed to support occupant comfort and health and building durability.
- Use renewable energy and energy recovery wherever possible.
- Design a flexible system that accommodates reconfiguration of interior space over time while maintaining original level of performance.

- Separate the delivery of ventilation air from heating and cooling, and integrate the monitoring of these systems for occupant comfort and energy effectiveness.
- Provide means for occupants to adjust thermal comfort conditions.
- Incorporate sufficient sensors and metering capability so that occupant and building operators can see, assess, and improve conditioning system performance.

Geothermal conditioning lends itself well to the application of these strategies. It provides a renewable source of thermal energy and a heat sink for heating, cooling and ventilation. With the exception of passive earth sheltering and earth tube ventilation systems, geothermal conditioning typically uses water or a water/antifreeze mix as an energy carrier for all or part of the system. Most geothermal conditioning systems are low-temperature/low-exergy systems and those that are not often use energy cascades with energy recovery to make effective use of higher temperature ground resources. The total savings from geothermal conditioning will vary widely depending on the local climate and subsurface temperatures, the conditioning strategy, and its design and operation. Nonetheless, because the ground temperature often approximates the average annual air temperature in a given location, a geothermal approach is likely to save energy wherever the average annual air temperature is closer to the building balance point temperature than the outdoor temperature range.

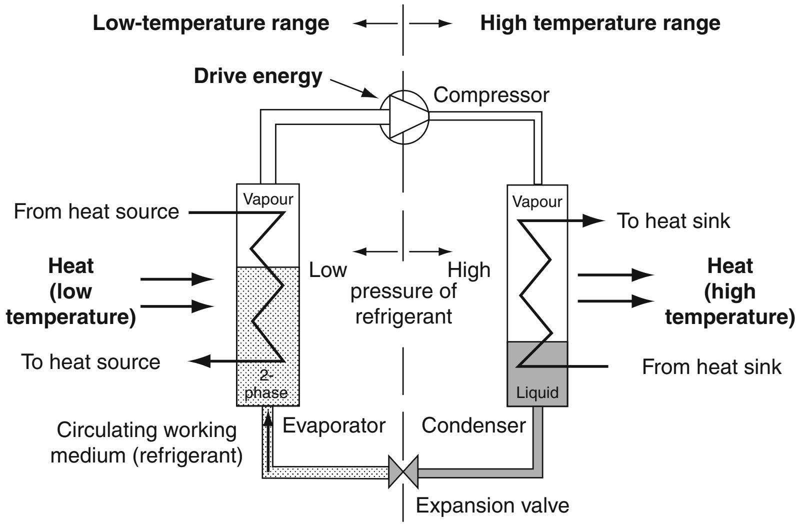
Discussions of geothermal conditioning often focus on heat pumps as the interior delivery system. One reason for this is that heat pumps operate efficiently at temperatures commonly accessible at and within a few meters below a building foundation. In addition, even when a heat pump's energy consumption is evaluated as source or primary energy rather than site energy, its efficiency usually exceeds 100%. (Note: Primary or source energy is the energy value based on source fuel inputs. For electricity, this is the energy value of the oil, natural gas, coal, or other source fuels used to generate the electricity and is typically 3.0–3.5 times higher than the energy value of the electricity at the building site.) This is because the heat pump can use heat in the ambient air, ground, or water to cause certain refrigerants to vaporize and to reach a much higher temperature when compressed. Low-grade heat coupled with a refrigerant cycle allows the heat pump to supply heat to or absorb heat from a building with a fraction of the energy required by combustion heating or conventional air conditioning.

In the case of a geothermal heat pump, the heat is being transferred from and to the ground or ground-coupled water. In heating mode, a compression heat pump transfers the earth's thermal energy, often in the range of 10–15°C, to a refrigerant that evaporates as the heat is absorbed and becomes a gas. The refrigerant gas then passes through a compressor where it is pressurized. This increases its temperature, generally above 71°C. The heated gas then passes through another heat exchanger, transferring its heat to air or water being used to heat the interior space, often at 38–43°C. As the refrigerant gas loses heat, it condenses back to a liquid, is cooled as it passes through an expansion valve, and is then ready to repeat the cycle (see Fig. 5). A reversing valve allows the heat pump to change the direction of refrigerant flow, causing heat from the indoor space to be transferred to the refrigerant and later to the ground. Compression heat pumps are by far the most common, but absorption and adsorption heat pumps also exist. Like compression heat pumps, absorption heat pumps use low-grade heat to vaporize a refrigerant, but use thermal energy rather than electricity to compress the refrigerant. Adsorption heat pumps, still in development, also use thermal energy to drive the process [17]. Heat pumps and their operation are extensively discussed in several sources [18–20], but their efficiency is a key aspect of their sustainability and is briefly summarized here.

The efficiency of the heat transfer process is the ratio of the energy used to drive the process to the amount of heat transferred. This is called the coefficient of performance or COP. In heating mode, the COP is the ratio of heat supplied to energy used. In cooling mode, the COP is the ratio of heat removed to the energy used [22].

$$\text{COP} = \text{Heat Supplied or Heat Removed (kW)}/\text{Power Input(kW)}:$$

As an example, a geothermal heat pump that provides 12 kW of heat output with 3 kW of electricity has a heating COP of 4. This means that one part electrical energy and three parts ground thermal energy supply four parts of usable energy. On a site energy basis, this



Geothermal Conditioning: Critical Sources for Sustainability. Figure 5
Diagram of vapor compression heat pump in heating mode [21]

means that the heat pump efficiency is 400%. When considered from a source or primary energy perspective, and assuming a 30% source to site conversion efficiency for electricity, the source efficiency of this heating process is 120% (30 × 400%). The COP given by the manufacturer is determined under specific operating conditions that usually vary from those on site. Manufacturer COPs typically range from 3 to 6 at present.

The efficiency of heat pumps over the course of a year under actual operating conditions and considering auxiliary system components such as circulation pumps is expressed as the seasonal performance factor (SPF) or average annual COP. The SPF is the ratio of the system's usable energy output to the energy input.

$$\text{SPF} = \text{annual usable energy output (kWh)}/\text{annual energy input (kWh)}$$

This measure more accurately describes system performance and is often lower than the equipment's rated performance for several reasons. Commonly, a heat pump that provides heating and cooling is sized for the dominant load. This may mean that a heat pump with sufficient heating capacity, for example, is oversized for cooling and therefore operates less efficiently in cooling mode. In addition, a system often does not operate at the temperatures at which it is rated but rather under more variable temperatures that decrease its efficiency. Cited SPFs for geothermal heat pumps vary considerably, but may be in the range of 3.3–4.3 [23]. Because a heat pump is able to derive a substantial portion of its heating energy or heat removal capacity from ambient air, the ground, or groundwater, its efficiency generally exceeds that of any other mechanical conditioning equipment powered by nonrenewable energy, even when the source to site conversion efficiency of the power source is much higher than that for electricity, for example, natural gas [24].

A heat pump's ability to heat and cool makes it effective in distributed systems (also known as unitary systems), particularly in mixed-use buildings. In fact, a distributed approach tends to be more energy efficient [25]. In a mixed commercial/residential building with multiple heat pumps connected to a single internal water loop, heat pumps in commercial zones with high internal loads might be in cooling mode while those in residential zones are heating. Because a heat pump in cooling mode returns warmer water to the internal loop and a heat pump in heating mode returns cooler water to the loop, the temperature of the internal loop will be self-balancing to some extent, remaining in a temperature range favorable for efficient heat pump operation for an extended time period. This reduces the need for heat transfer between the external (ground) loop and internal loop and thus the pumping energy required. Either alone or in combination with other low-exergy equipment such as radiant wall, floor or ceiling panels or fan coil units, heat pumps can be flexibly configured to deliver thermal comfort efficiently and close to the point of use. See Fig. 6 for a geothermal heat pump system design strategy/guideline, developed by Kavanaugh [26].

Heat pumps are not, however, a component of every geothermal conditioning strategy. By focusing on the thermal properties of soil, rock, and water, a host of strategies has been developed to couple building heating and cooling with the ground and ground-coupled fluid. Tables 4 and 5 list many available options. Each capitalizes on the capacity of the ground or ground-coupled water to absorb and supply substantial thermal energy while maintaining a fairly constant temperature year-round. (Note: UTES systems are the exception; they may be designed to concentrate thermal energy for seasonal use, as described later in this section.) The basic components of each approach are (a) the ground coupling through which thermal energy is transferred to and from the ground and (b) the internal system through which thermal energy is distributed from or to the ground for comfort conditioning. Because this entry focuses on the earth's thermal energy for sustainable conditioning, Tables 4 and 5 emphasize ground coupling options. Table 4 lists closed loop systems in subsurface soil and rock and Table 5 lists water-based systems, both open and closed loops. Within the system descriptions and examples, however, internal system options are often discussed.

Like solar conditioning, geothermal conditioning can be passive or active. In essence, every building in contact with the ground exchanges heat with it, intentionally or not. In fact, any ground-based construction, including roads and pavement, alters the ground's thermal profile by changing characteristics such as albedo, reflectivity, and rainwater absorption, and by adding heat transfer surfaces. Passive geothermal conditioning is by far the oldest approach listed, but like passive solar conditioning, it may be overlooked.

Active strategies are more numerous and can be subdivided into approaches that use subsurface soil and rock for their ground coupling and those that use water. The effectiveness of a given approach will depend on site conditions and natural resources, the local geothermal gradient, and many project-specific variables. In recent years, system designers have also developed approaches that derive their thermal stability from a subsurface location (e.g., sewer pipe) while the source of their thermal energy may be other than geothermal, for example, residual heat in building wastewater.

With the exception of earth sheltering and earth tube ventilation systems, geothermal conditioning approaches use a fluid as the energy carrier or heat transfer medium between the outdoor and indoor system components. The interface between the outdoor and indoor components is often a heat exchanger or heat pump, although other types of equipment are possible. Ground sources that provide higher temperature heat (e.g., >30 C) must interface with something other than a heat pump because the maximum input water temperature for a heat pump is approximately 32°C and its efficiency is compromised at these higher temperatures. In open loop water-coupled systems, a heat exchanger is recommended as a buffer between the external water source and the indoor conditioning equipment because of the lively chemistry and/or biology of these water supplies [27].

All of the geothermal conditioning approaches in Tables 4 and 5 take advantage of the earth's stable, low-grade thermal energy and its heat capacity. Most systems use these ground characteristics for energy exchange, to provide a heat source and heat sink for the building. Some approaches target thermal storage only. Given the range of options available and an increasing emphasis on low-exergy conditioning technologies, one or more geothermal conditioning approach is probably feasible in most buildings.

Subsurface Soil and Rock Systems

With the exception of earth sheltering, subsurface soil and rock systems use a fluid enclosed in pipe to transfer heat between the building and the outdoors. For earth tubes, that fluid is air and for other systems, refrigerant, water, or a water/antifreeze mix. Under normal operating conditions, there is no direct contact between the fluid and the subsurface environment and this type of

Geothermal Conditioning: Critical Sources for Sustainability. Figure 6
Strategy for geothermal heat pump system design. *GCHPs* ground-coupled heat pumps (soil-based systems), *GWHPs* groundwater heat pumps, *SWHPs* surface water heat pumps

Geothermal Conditioning: Critical Sources for Sustainability. Table 4 Subsurface soil and rock systems (all closed loops)

<table>
<tr><th>Passive or active strategy</th><th>Exterior equipment/ configuration</th><th>Typical depth</th><th>Energy carrier</th><th>Function</th><th>Exterior/interior interface</th></tr>
<tr><td>Passive</td><td>Earth berms</td><td>At grade or foundation depth</td><td>Soil</td><td>Insulation, thermal mass, reduced infiltration, reduced solar gain</td><td>Building enclosure</td></tr>
<tr><td rowspan="7">Active</td><td>Earth tubes</td><td>3–5 m</td><td>Air</td><td>Preheating or cooling of ventilation air</td><td>Energy recovery ventilator; possibly UV disinfection</td></tr>
<tr><td>Horizontal trench with straight pipe or slinky coil</td><td>1–2 m</td><td>Water–antifreeze mix</td><td rowspan="5">Energy exchange for heating and/or cooling</td><td>Heat pump</td></tr>
<tr><td>Direct connection to conditioning equipment</td><td>1.2–2 m</td><td>Refrigerant</td><td>Heat pump</td></tr>
<tr><td>Building foundation piles (open or closed)</td><td>5–30 m</td><td>Water or water–antifreeze mix</td><td>Heat pump or heat exchanger</td></tr>
<tr><td>Shallow vertical boreholes with U-tube pipe</td><td>30–120 m</td><td>Water or water–antifreeze mix</td><td>Heat pump</td></tr>
<tr><td>Deep vertical boreholes with coaxial pipe</td><td>1,000–3,000 m</td><td>Water</td><td>Heating equipment or heat exchanger (typically cooling not attempted with deep systems)</td></tr>
<tr><td>BTES (borehole thermal energy storage)</td><td>20–300 m</td><td>Water or water–antifreeze mix</td><td>Seasonal hot or cold storage for increased efficiency</td><td>Heat pump, heat exchanger, cogeneration power plant, solar hot water system</td></tr>
</table>

sealed subsurface pipe heat exchanger is called a closed loop system.

Design and sizing of the ground heat exchanger is a key aspect of system cost and performance. The characteristics of underlying soils and rock, ground moisture content and water movement are among the variables that affect ground temperature and heat transfer and these can be difficult to model with precision. Research has also shown that in low-temperature systems, the effectiveness of the ground heat exchanger is strongly associated with its heat transfer over time, particularly when multiple heat exchanger pipes are in close proximity [28]. Abundant research focuses on this topic and many sizing calculations, modeling tools, and rules of thumb exist to support this task [13, 29]. It is worth noting, however, that the validity of available sizing methods is still debated by those who design and operate closed loop systems [30]. Data from operating systems are also lacking [31]. Despite these challenges, the majority of ground-coupled systems now being installed are closed loop systems [32]. Brief descriptions of soil- and rock-based systems and installed examples are offered below.

Earth Sheltering The simplest form of geothermal conditioning is the passive strategy of earth sheltering,

Geothermal Conditioning: Critical Sources for Sustainability. Table 5 Water-based systems (all active strategies, both closed and open loops)

Water source	Open or closed loop	Exterior equipment/ configuration	Typical depth	Energy carrier	Function	Exterior/ interior interface
Aquifer	Open	Supply well with surface discharge	15–100	Groundwater	Energy exchange for heating and/or cooling	Heat exchanger
		Supply and injection wells, shallow or deep	15+	Groundwater		Heat exchanger, cooling or heating equipment
		Standing column (or coaxial) well	120–375 m	Groundwater		Heat pump
		ATES (aquifer thermal energy storage)	10–400 m	Groundwater	Seasonal hot or cold storage for increased efficiency	Heat exchanger
Surface water (ocean, lake, river)	Open	Supply and reinjection pipe	Varies by water body; ideally at depth where temperature is stable and where reinjection does not affect natural seasonal cycling	Surface water	Energy exchange for heating and/or cooling	Heat exchanger
	Closed or Open	Slinky coil	3–3.5 m minimum; sufficient depth so that supply temperature always $>4°C$	Water or water–antifreeze mix		Heat pump or heat exchanger
Abandoned mine tunnels	Open	Supply and reinjection pipe	Varies with mine	Groundwater	Energy exchange for heating and/or cooling	Heat exchanger, heating or cooling equipment
	Open	CTES (cavern thermal energy storage)	Up to 2,000 m	Groundwater possibly with phase change material	Seasonal hot or cold storage for increased efficiency	
Sewer infrastructure	Closed or Open	Heat exchanger within/around pipe	Standard sewer pipe depth for given location	Water or water–antifreeze mix	Energy exchange for heating and/or cooling	Heat pump
Water treatment infrastructure	Open	Supply and reinjection pipe	Surface or subsurface pipe	Treated wastewater	Energy exchange for heating and/or cooling	Heat exchanger

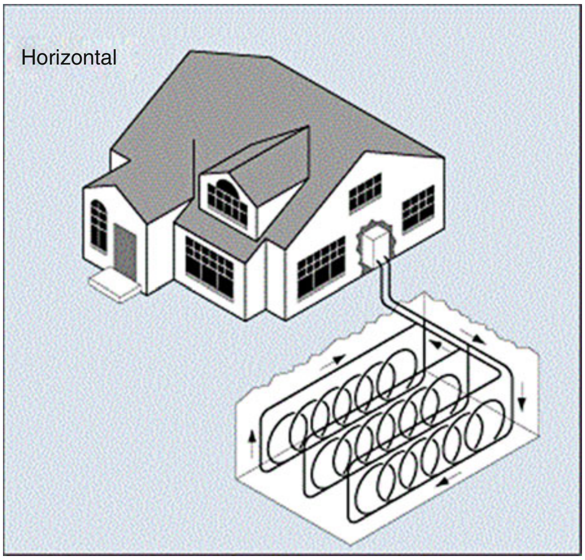
also called earth berming or earth integration. Ground temperatures begin to converge on a steady value just 30–50 cm below the surface [8]. An earth-sheltered building enclosure at and below this depth experiences temperatures that vary only a few degrees throughout the year and will generally be warmer in winter and cooler in summer than the outdoor temperature. The constant temperature, together with the reductions in air leakage and in convective and conductive heat loss that accompany earth sheltering, can substantially reduce mechanical conditioning requirements. The effectiveness of earth sheltering is well established, but its use requires careful attention to orientation, structure, waterproofing, daylighting, and egress as well as the standard range of design considerations. Although current enclosure design strategies focus largely on reducing heat transfer at the foundation, there may be substantial room for development or redevelopment of passive geothermal conditioning strategies [33].

Earth Tubes (also called Earth Pipes or Earth-to-Air Heat Exchangers)

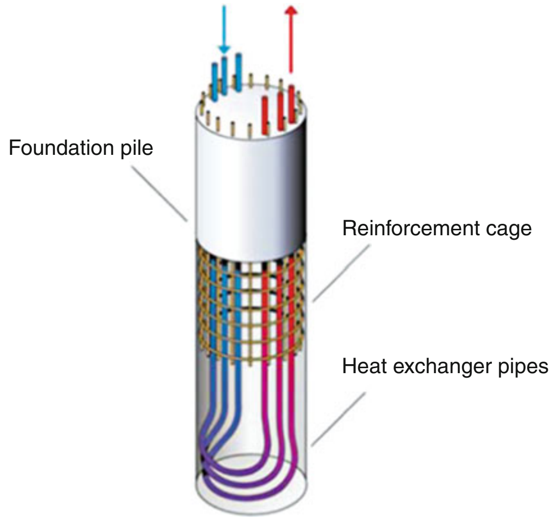
Earth tubes are buried pipes through which outdoor air is drawn into the building. The earth's temperature can heat the air in winter and cool it in summer, reducing the energy required to condition ventilation air and in some instances, eliminating the need for additional cooling equipment. Monitoring data for earth tube systems are still limited, but Pfafferott [34] offers a comparative analysis of the performance of systems installed in three buildings in Germany between 1999 and 2001. He found that each system supplied far more heating and cooling energy than the primary energy used by the fans and that the ground characteristics and the impact of the building on ground temperature were as important as the earth tube diameter on thermal efficiency. To avoid unwanted heating in summer and cooling in winter, a control strategy is necessary. In some systems, permeable pipe is used to allow condensation within the tubes to evaporate and UV filtration is used to address mold or bacteria the may be in the air stream. Where radon is a concern, care must also be taken that the earth tubes are not transferring radon gas from the ground into the ventilation system [35].

Horizontal Trench, Pipe, or Slinky Coil Small building loads can be handled with a horizontal ground heat exchanger installed below the frost line (Fig. 7). Since trenching is less expensive than drilling, horizontal installations cost less but require more land area; increased temperature fluctuations at shallower depths (1–2 m) mean that increased pipe length (heat transfer surface area) is required. Because of the land area requirement, horizontal ground heat exchangers typically serve building loads less than 175 kW.

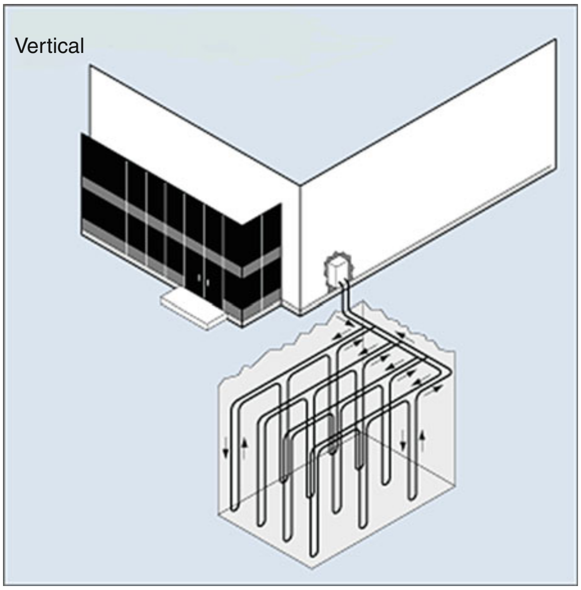
Building Foundation Heat Exchangers (foundation piles, energy piles, slot-die walls): Structural components such as piles, retaining walls, and foundation slabs can be used to exchange thermal energy between the ground and the building. Fluid-filled pipe systems are incorporated inside the foundation elements and serve a purpose similar to vertical borehole exchangers, but within the building's footprint. Relatively new (1990s) as a design strategy, foundation piles may be steel, precast concrete, or cast in place concrete [36]. The piles contain two or more U-tubes (see Fig. 8) that are connected either directly (open) or indirectly (closed) to the building's mechanical system. Pump



Geothermal Conditioning: Critical Sources for Sustainability. Figure 7
Horizontal ground heat exchanger



Geothermal Conditioning: Critical Sources for Sustainability. Figure 8
Building foundation pile heat exchanger [38]



Geothermal Conditioning: Critical Sources for Sustainability. Figure 9
Vertical borehole heat exchanger

energy is minimized since the heat exchanger is within the building footprint. Currently, design of these systems is adapted from vertical borehole design and because of uncertainties about the mechanical behavior of the soil over time (thermoelasticity and soil strength with heating and cooling), substantial safety factors are built into these systems, resulting in high costs [37].

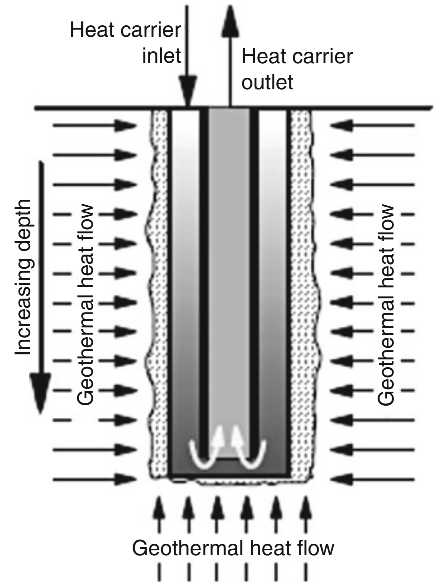
Vertical Boreholes, Shallow The most common type of closed loop ground heat exchanger is a shallow vertical borehole system. Borehole diameters vary by pipe size and by construction convention, which differs by country to some extent. In the United States, a typical borehole is about 10–15 cm diameter. The depth may range from 30 to 120 m, depending on several factors such as the conditioning load, available land area, ground conditions and temperature, and drilling costs. A U-tube or ground probe, usually of high-density polyethylene (HDPE) pipe and often 19–25 mm pipe diameter, is inserted into each borehole (see Figs. 9 and 10) and the borehole should be packed and sealed with grout, at least at the surface, to prevent surface contaminants from passing easily down the borehole and into groundwater. (Note: Requirements for grout vary, although the potential for surface contaminants to reach groundwater more easily through

Geothermal Conditioning: Critical Sources for Sustainability. Figure 10
HDPE U-tube for vertical borehole [40]

a borehole does not. Grouts with improved heat transfer characteristics are available.) The total underground pipe length must provide sufficient heat transfer to satisfy the connected peak block load, which is the maximum cooling or heating load, whichever is greater, imposed on the conditioning equipment during the cooling or heating season. (Note: If the building has good load diversity, the peak block load will be less than the sum of the peak room loads or peak zone loads.) Except where borehole thermal energy storage (BTES) is used, boreholes are often spaced 4.5–6 m apart so that heat transfer with the ground is not compromised by proximity to other boreholes. A radial configuration for shallow boreholes has also been developed [39].

Vertical Boreholes, Deep Deep borehole systems, 1,000–3,000 m, capitalize on higher ground temperature at depth and so are predominantly used for heating. In this type of system, an insulated production pipe is inserted into a borehole casing sealed at the bottom, providing a concentric pipe configuration. The heat transfer fluid, typically water that may be treated with a corrosion inhibitor, is pumped down the borehole casing, and up through the central production pipe (see Fig. 11). There is no direct contact between the heat transfer fluid and the subsurface soil and rock; the fluid gains heat at depth according to the geothermal gradient. At well exit, the heat transfer fluid passes through a heat exchanger, heat pump, or other heating equipment, depending on the fluid temperature (±40°C). The higher cost of deep borehole systems makes them better suited to serve the base load in systems that have sizable heat demand (see Fig. 12) [41].

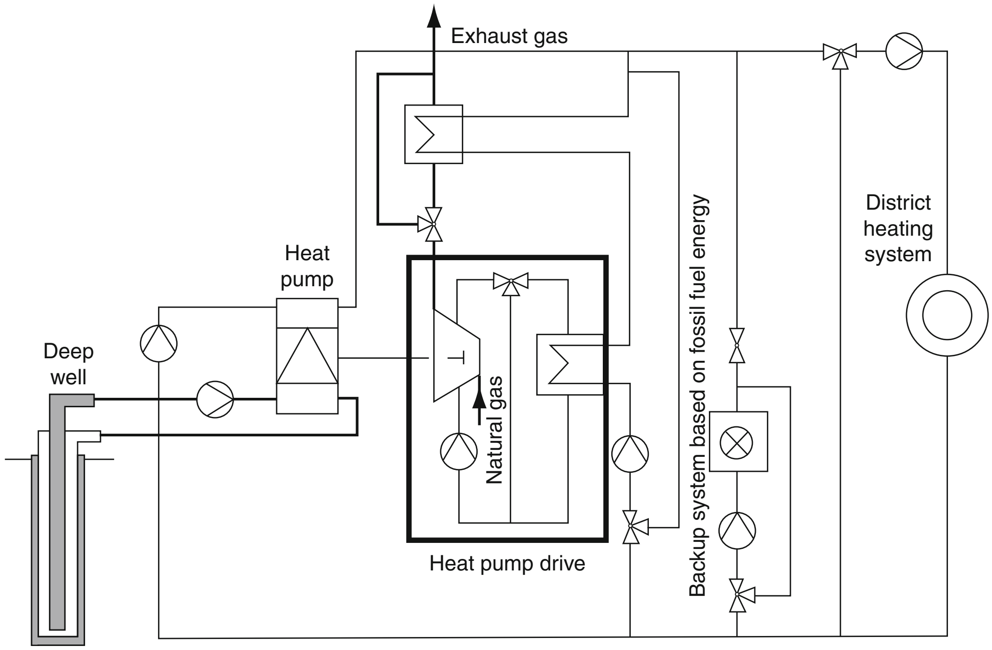
Borehole Thermal Energy Storage Borehole thermal energy storage, BTES, is a type of underground thermal energy storage (UTES) system used to concentrate heat and cold for seasonal use. For a BTES, vertical boreholes are placed in close proximity (1.5–3 m apart) to seasonally charge the system with hot or cold fluid. In summer, for example, a heat pump or other mechanical device can transfer heat to the ground for winter heating. In winter, that heat can be extracted and the ground can be charged with cold fluid for summer cooling. For efficiency, different ground areas or depths are often used for hot and cold storage. Although some heat or cold is lost at the system edges and at the ground surface, these systems can be used successfully in existing subsurface rock and soil; constructed storage vessels are not required. From a cost standpoint, underground thermal energy storage systems, including BTES, ATES, and CTES systems, tend to work best for small district systems rather than for single buildings.



Geothermal Conditioning: Critical Sources for Sustainability. Figure 11
Deep borehole heat exchanger [42]

Examples of Subsurface Soil and Rock Geothermal Systems *Earth Tubes*: Fraunhofer ISE, Freiburg, Germany: Installed in 2001, the earth-to-air energy exchanger provides cooled or preheated air with a ground temperature of 13.8°C. This open loop system consists of seven polyethylene ducts, 90–100 m long and 250 mm in diameter, buried 4–5 m and partially below the foundation slab. The air speed is 5.6 m/s and mean airflow is 7,000 m^3/h. The system is controlled by air temperature at the inlet and does not operate between 12°C and 16°C. During a 1-year analysis of the system from November 2001 to October 2002, the COP was 29 kWh_{th}/kWh_{mech}, high enough to supply more heating and cooling energy than the primary energy used for fans, with a fan efficiency of 70% [34].

Vertical Borehole Heat Exchanger: In 1993, a 2.2 MW vertical borehole heat exchanger was



Geothermal Conditioning: Critical Sources for Sustainability. Figure 12
District system served by deep borehole exchanger [41]

installed at Richard Stockton College in Pomona, New Jersey (USA) to allow replacement of aging gas-fired heaters and electric compressor type coolers with geothermal heat pumps. A total of 400 boreholes 425 ft (129.54 m) deep and approximately 4.5 m apart were installed under an existing parking lot and adjacent open area. Each 10 cm borehole contains a single 3.25 cm diameter HDPE plastic U-tube pipe and is sealed with clay slurry. Twenty lateral supply and return pipes channel the water circulating through the boreholes to central building where they are combined into 16 in. (40.64 cm) supply and return lines that serve heat pumps (35–123 kW) in campus buildings. The system reduced natural gas consumption approximately 75% and electricity consumption 25%, despite the switch to heat pumps. Since 1993, the college has added substantial geothermal conditioning infrastructure, both closed and open loop systems, and in 2008, an aquifer thermal storage system [43]. Extensive monitoring of system performance and ground/groundwater conditions is conducted.

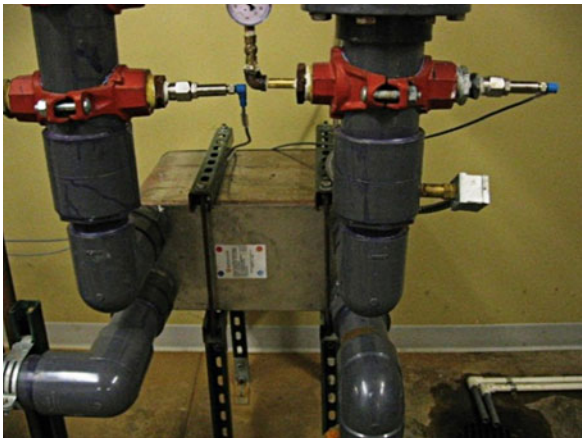
Building Foundation Piles: The nursing school at Sapporo City University in Japan, completed in 2006, uses steel foundation piles filled with water to provide a ground heat exchanger that supplies the building's base heating and outdoor air cooling loads. For a floor area of 2,800 m^2, 51 piles from 600 to 800 mm diameter were drilled 4 m into the ground. Two U-tubes were inserted in each pile and the pile was filled with 115 m^3 water. The manifold system for the piles feeds a 50 kW heat pump that provides both heating and cooling. Three vertical boreholes 75 m long supplement the system so that the ground heat exchanger system can meet the base heating load of 50 kW and the base cooling load for outside air. During 2007, the piles extracted 43,929 kWh of heat from the ground in winter and transfer 53,939 kWh of heat into the ground in summer [36].

Borehole Thermal Energy Storage (BTES): The Drake Landing Solar Community in Okotoks, Alberta (Canada) relies on the earth's high volumetric heat capacity to store heat captured with solar hot water systems in summer months and to provide heat throughout Alberta's cold winter. Opened in 2007, the Drake Landing project is a district system serving 52 well-insulated single-family homes. Heat from 800 single-glazed roof-mounted solar hot water panels is fed to a seasonal thermal storage system that consists of 144 vertical boreholes approximately 30 m deep. The borehole field was anticipated to require 5 years to fully charge to 80°C by summer's end, thereby allowing it to supply 90% of the community's heating energy (90% solar fraction). However, 3 years after it began operating, the system reached 80% solar fraction and should be fully charged in 2011. Fan coil units are the terminal heating equipment in each home [44].

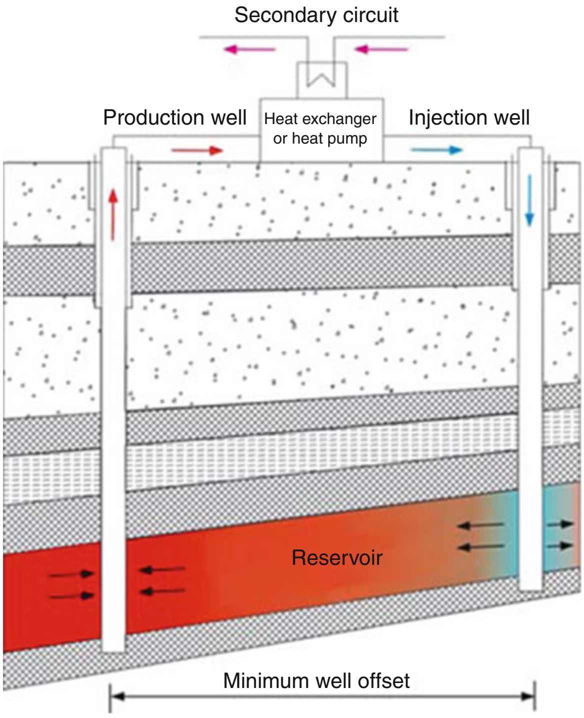
Water-Based Systems

Water-based systems use water that originates outside the building – generally groundwater or surface water – as the energy carrier. With a few exceptions, this externally sourced water is piped to the building where it transfers heat in direct contact with some component of the conditioning system: a heat exchanger, heat pump, or other conditioning equipment (see Fig. 13). It is then piped away from the building for release to or near the original water source and usually at a temperature within 6°C of its source temperature. This is called an open loop system. Closed loop water-based systems bring building piping to the external water source such as a pond or lake. Like other closed loop systems, the building piping is filled with a fluid that transfers heat between the building and the outdoors and there is no direct contact between the external water source and the heat transfer medium in the building pipes.

The reason for emphasizing direct contact between an external water supply and the building mechanical equipment, or the lack thereof, is that water is an excellent solvent that "dissolves more substances in greater quantities than any other liquid" [45]. Water will react with pipes and equipment, and natural water such as groundwater or surface water contains minerals and microbes from surrounding soil and rock that can promote those reactions, particularly in the presence of oxygen (see Fig. 15). Whereas equipment connected to the municipal water supply is often treated with chemicals to control chemical and biological activity (e.g., cooling towers),



Geothermal Conditioning: Critical Sources for Sustainability. Figure 13
Brazed plate and frame heat exchanger in 4,000 m^2 mixed-use building. Water's remarkable heat capacity allows smaller mechanical system components than those required by air-based systems [47]



Geothermal Conditioning: Critical Sources for Sustainability. Figure 14
Open loop aquifer system with production and injection well [48]

Geothermal Conditioning: Critical Sources for Sustainability. Figure 15
Heat exchanger fouling from excessive iron in groundwater [49]. Failure to test groundwater prior to system installation may result in a system too maintenance-intense to operate economically

equipment connected to a natural water supply cannot be handled the same way. This characteristic is understood and addressed in water well literature, but underemphasized in building systems literature and should not be ignored in practice when sustainability is the goal [46].

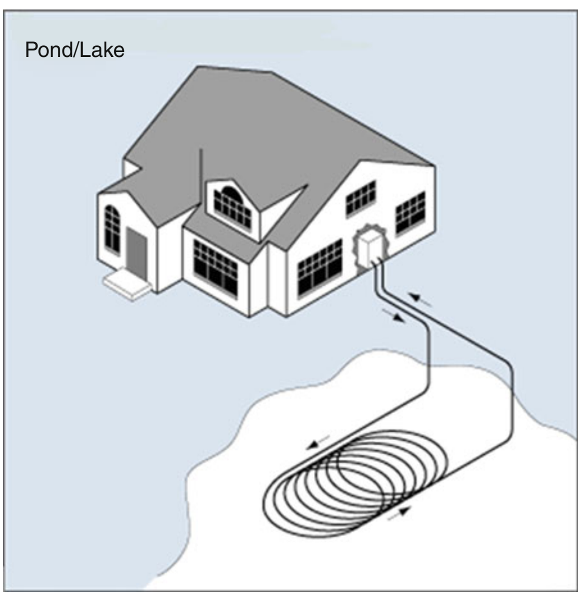
As with subsurface soil and rock systems, the design and sizing of the heat exchange system is a key aspect of overall cost and performance. One obvious prerequisite is the proximity of a suitable water source. Local regulations must also support the use of such systems. In groundwater applications, the water is pumped from an aquifer at stable temperatures similar to the ground temperature at that depth and is discharged either to surface water or to the same aquifer. Ease of access, water quantity, water quality, and viable discharge options are the limiting factors. In surface water applications, which can be either open or closed loops, water temperature and quantity are essential factors for effective heat exchange. The water temperature must not fall below 4°C and must remain in an efficient range for cooling (preferably <23°C) regardless of solar radiation and other heat transfer to the water. For open loop surface water applications, water quality is also important and can vary seasonally and during storms. Whereas soil- and rock-based heat exchangers are estimated to have a heat output of 20–50 W/m^2, the heat output of groundwater and surface water systems is estimated to be 2,300–4,600 W/m^3/h [18]. Brief descriptions of water-based systems and installed examples are offered below.

Aquifer-Based System Before the development of plastic pipe that could be used for closed loop systems, aquifer-based open loop geothermal systems predominated. Two primary configurations exist: those that reinject the water into the ground, usually into the source aquifer (Fig. 14), and those that discharge to surface water (pump and release or, colloquially, pump and dump systems). Well depths may range from 15 to 100+ m and flow from 1 to 125+ L/s.

Because they require less exterior infrastructure, aquifer-based systems need less land area and have lower first costs. Conventionally, the considerations in choosing an aquifer-based system include proximity to the building site; groundwater availability/quantity, depth and flow rate; water chemistry; the conditioning system temperature drop and load factor; and the groundwater discharge strategy. Today, however, a primary consideration for the sustainability of these and all other groundwater applications may be the protection of drinking water resources. Groundwater is a preferred source of drinking water, but lax or nonexistent groundwater regulation in the past and even at present has allowed contamination and depletion of known aquifers. Population growth compounds these problems. Although some aquifer-based systems have been operating for decades without dropping the groundwater table, ongoing use of aquifer water for any application must consider its impact on future drinking water supplies.

Standing Column or Coaxial Well A standing column well (SCW) is an open loop system that draws and reinjects to the same well. SCWs are generally used where bedrock is close to the surface. The ground heat exchanger is a vertical well typically 150 mm diameter in bedrock with a 200 mm steel casing in the overlying unconsolidated layer. In shallower wells, the submersible pump is at the bottom of the well with the return near the top. In wells deeper than 150 m, return is generally via a 100 mm PVC dip tube that extends to the well bottom and is perforated for the last 6–18 m. A distinct characteristic of these wells is the practice of "bleeding" the well to control the temperature. Where freezing is possible, the well may be bled, typically with surface disposal, to draw warmer water into the well. Bleeding may also be used if the well is overheating in summer. SCWs connect directly to a geothermal heat pump and in residential systems may also provide domestic water.

Surface Water System The diverse thermal profile of surface water bodies results in similarly diverse strategies for surface water geothermal conditioning. Surface water systems can be either open or closed loops. They can be as shallow as a pond and as deep as the ocean (e.g., the Hawaii Gateway Energy Center, described below). In closed loop systems, water or a water/antifreeze mix is pumped through a submerged pipe loop that transfers heat to and from the body of water (see Fig.16). Compared to soil-based closed loop systems, water-based systems have lower excavation costs and usually lower costs for pumping and for overall operation and maintenance. Temperature variations in surface water are typically far greater than those in soil,



Geothermal Conditioning: Critical Sources for Sustainability. Figure 16
Closed loop surface water exchanger

however, so the system may be less efficient and at greater risk for freezing and other damage if the piping is accessible and/or close to the surface. In open loop systems, the surface water body is often used for a heat sink, similar in function to a cooling tower but without the noise, fan energy, chemical dosing, and maintenance demands. Direct cooling or precooling of ventilation air is also possible by pumping water at 10°C or below through a coil within a return air duct or convector system.

Aquifer Thermal Energy Storage Similar to BTES, aquifer thermal energy storage (ATES) is a means to concentrate heat and cold underground for seasonal use. A series of injection wells is used to inject either heated (13–120°C) or cooled (6–12°C) water for later withdrawal. Heat and cold can be stored at different depths if the underlying geology permits. Withdrawal can occur through the same wells, or through separate ones, in which case the water flows in the aquifer between injection and supply. China began installing large open ATES systems (surface water allowed to infiltrate groundwater) for cold storage in the 1960s [50]. The longest operating high-temperature system was installed at Ultrecht University in the Netherlands in 1991, using residual heat from cogeneration. Estimates of energy savings from ATES are quite high: 80% reduction in cooling costs and 40% reduction in heating costs [51]. Research indicates that a large percentage of land area is underlain by aquifers that could be used for ATES [51].

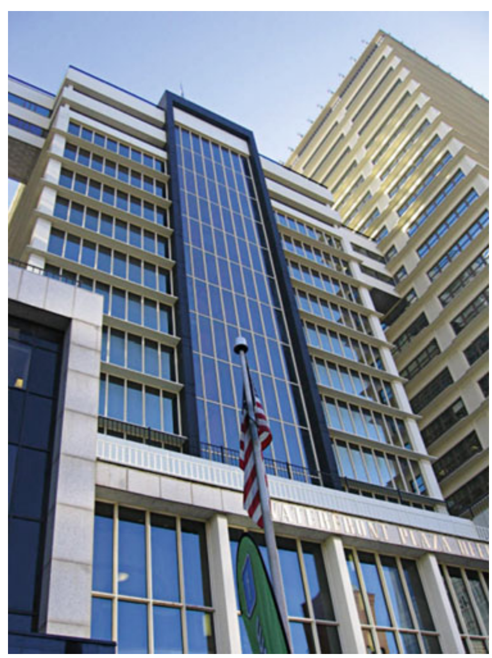
Abandoned Mine Tunnel/Cavity Systems Abandoned underground mines and tunnels accumulate groundwater. Depending on their size, these cavities can thermally function like an aquifer, providing an underground reservoir at a stable temperature. Cavity thermal energy storage (CTES) systems typically use supply and injection wells. In some cases, environmental regulation (e.g., in the USA) require that groundwater in mine tunnels be treated for surface discharge. Where this occurs, a water treatment infrastructure system (see below) may be possible.

Sewer and Water Treatment Infrastructure Systems Sewer pipes and municipal or industrial pipes that carry treated water to its discharge point are typically buried and benefit from the ground's thermal stability and capacity. In addition, the processes that serve these pipes add heat energy so that the fluids they carry often have thermal energy content comparable to or higher than groundwater (>10°C). Although water treatment pipes may not be colocated with the buildings they serve, sewer pipes are. With constant and sufficient flow, these pipes and/or the fluids they carry provide a heat source and heat sink for geothermal conditioning without the need for new ground infrastructure. At least one company manufactures concrete sewer pipe with embedded heat exchangers to permit noncontact heat transfer (see Fig. 17) [52].

Examples of Water-Based Geothermal Systems *Aquifer Geothermal System with Surface Discharge*: The Galt House Hotel and Waterfront Plaza Office Towers in Louisville, Kentucky (USA) use a 21 MW open loop heat pump system to condition approximately 185,806 m^2 of hotel, office, and apartment space (see Figs. 18 and 19). The system was initially installed in 1984 and has since expanded to its current capacity. Seven wells approximately 40 m deep supply groundwater at 14°C and approximately 46 L/s to a central network of seven plate and frame heat exchangers. The groundwater discharges to the Ohio River. Distributed heat pump loops serve the buildings' interior. Because the well pumps are close to the ground surface, the groundwater system is shut down when outdoor temperatures fall below 4°C and boilers supply the building loop during cold weather.

Geothermal Conditioning: Critical Sources for Sustainability. Figure 17
Sewer pipe with embedded heat exchanger [52]

Geothermal Conditioning: Critical Sources for Sustainability. Figure 18
Original Galt House Hotel on *left*; Hotel expansion on *right*, Louisville, KY (USA) [40]



Geothermal Conditioning: Critical Sources for Sustainability. Figure 19
Waterfront Plaza Office Towers, Louisville, KY [40]

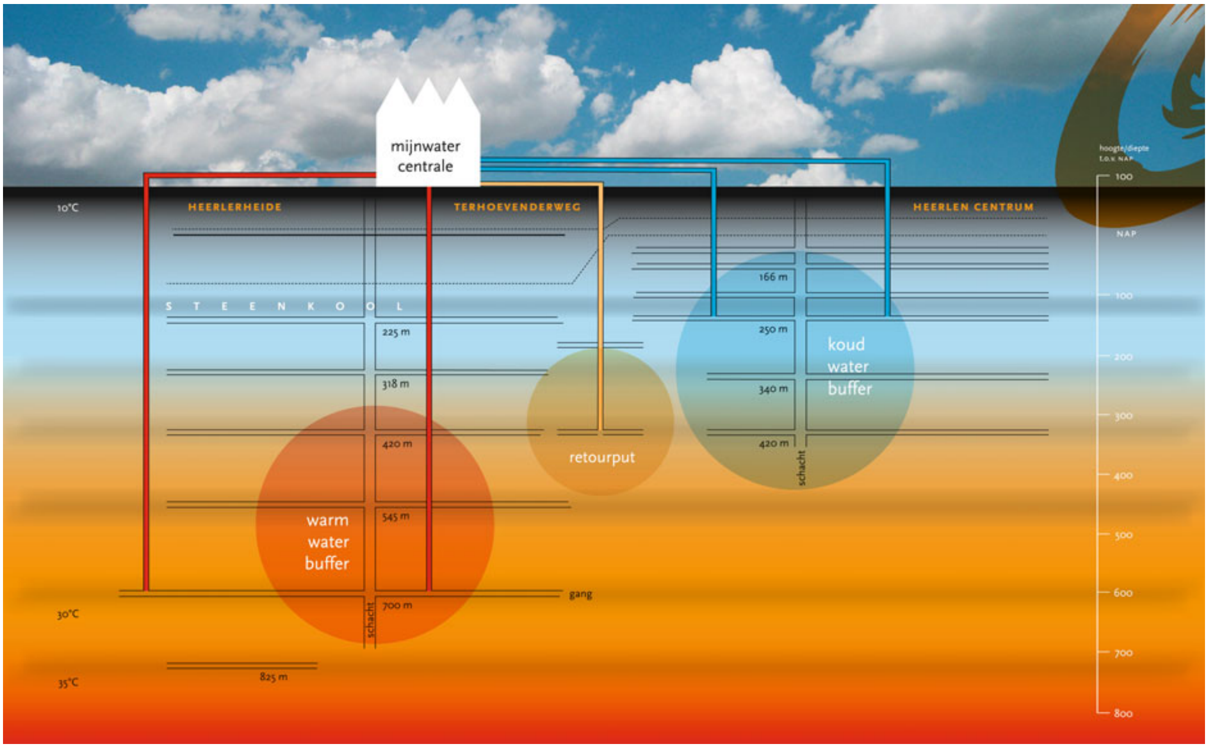
Seawater Direct Cooling: The Hawaii Gateway Energy Center (HGEC) visitor center on the south coast of Kona on the Big Island of Hawaii pumps seawater at 7°C from 914 m below the surface to cool the 334 m^2 building. The water is distributed through cooling coils in a subfloor plenum, absorbing heat from air supplied to the plenum through a dedicated air inlet structure. The conditioned air then rises through the building to thermal chimney outlet pipes for exhaust. This open loop seawater cooling system runs continuously throughout the day, providing 10–15 air changes per hour. Cooling coil condensate is collected and used for irrigation and toilet flushing. No auxiliary cooling equipment is used; only pump energy is consumed. HGEC produces more electricity than it uses (a net energy exporter) and the pump energy is supplied by a PV array.

Aquifer Thermal Energy Storage (*ATES*): At the Reichstag Building in Berlin, Germany, two confined aquifers at different depths are used for thermal separation and storage. The shallower aquifer ranges from 0 to 66 m depth and is served by two sets of five wells. The deeper aquifer lies at 270–370 m depth and is served by two wells 300 m apart. In summer months, residual heat from two combined heat and power (CHP) plants in the building charges the lower aquifer to approximately 70°C. During the winter, this water directly serves heating equipment at the beginning of winter and later, as the storage temperature drops during the heating season to 45°C, its temperature is boosted with an absorption heat pump. Meanwhile, the upper aquifer is charged with ambient cold during winter to a temperature of 10°C. In the summer, cooling needs are met with the cold storage and with an absorption heat pump serving as a chiller [53].

Mine Tunnel Geothermal District System with Cavern Thermal Energy Storage (CTES): In Heerlen, the Netherlands, flooded coal mine tunnels abandoned about 1960 are now part of a district geothermal system that provides conditioning to 350 homes and to businesses (see Figs. 20 and 21). Five wells 700 m deep serve a primary energy grid. Each well can supply almost 80 m^3/h at approximately 32°C. At distributed local "energy stations," heat exchangers transfer energy to the secondary grid that serves district buildings. Heat pumps, combined heat and power (CHP) equipment, and condensing gas boilers are used to add thermal energy for conditioning and domestic hot water, depending on the buildings' requirements. The system supplies low-temperature heating (35–40°C), high-temperature cooling (16–18°C) supply, and a combined return (20–23°C). The system includes both warm and cool thermal energy storage at 450 and 250 m depth, respectively [54].

Geothermal Conditioning: Critical Sources for Sustainability. Figure 20
Cultural Center: "Gen Coel" in Heerlen – home of mine tunnel geothermal district system [55]

Water Treatment Infrastructure: To supply a new geothermal heat pump district system, Oceana Naval Air Station in Dam Neck Annex, Virginia (USA) taps a pipe that carries 113,592 m^3 of 21°C treated wastewater to the ocean daily. The Hampton Roads Sanitary District (HRSD) owns the 1.6 m diameter concrete reinforced pipe that runs above and below ground across Navy property carrying the treated water 2.4 km into the Atlantic Ocean.



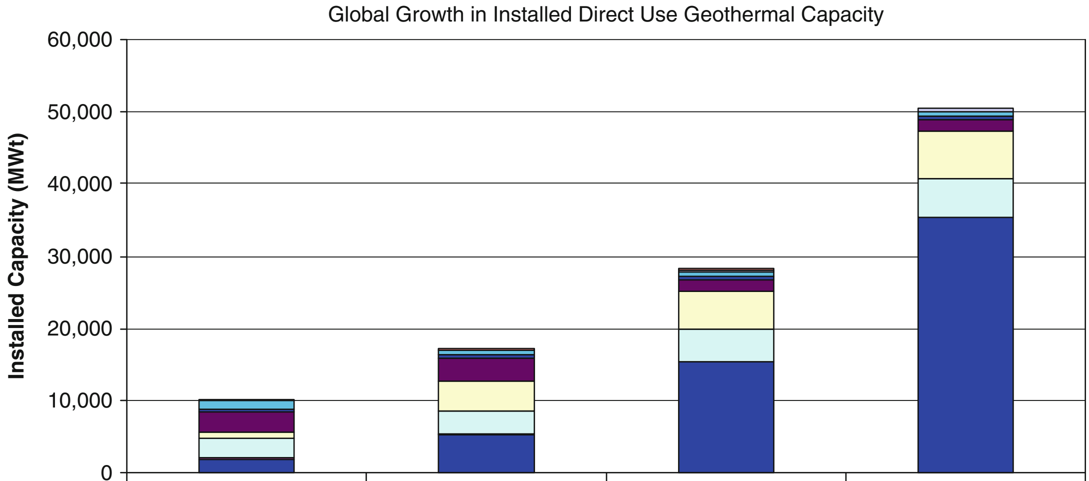
Geothermal Conditioning: Critical Sources for Sustainability. Figure 21
Schematic diagram of Heerlen subsurface system [55]

In a planned conversion from a central steam plant to a 1.6 MW geothermal heat pump coupled with a 14.5 MW cooling water condenser loop, the Navy avoided the installation of a 2,100 vertical borehole ground heat exchanger by using the treated wastewater. Almost 53,000 m^3 of the wastewater flow through four plate and frame heat exchangers daily and are returned to the pipe within 1.7°C of the supply temperature. Sixty-five percent of the base is currently on the new system, which is expandable. In its first year of operation (2009), the system reduced energy consumption for building conditioning by 40%.

Installed Capacity and Annual Energy Use

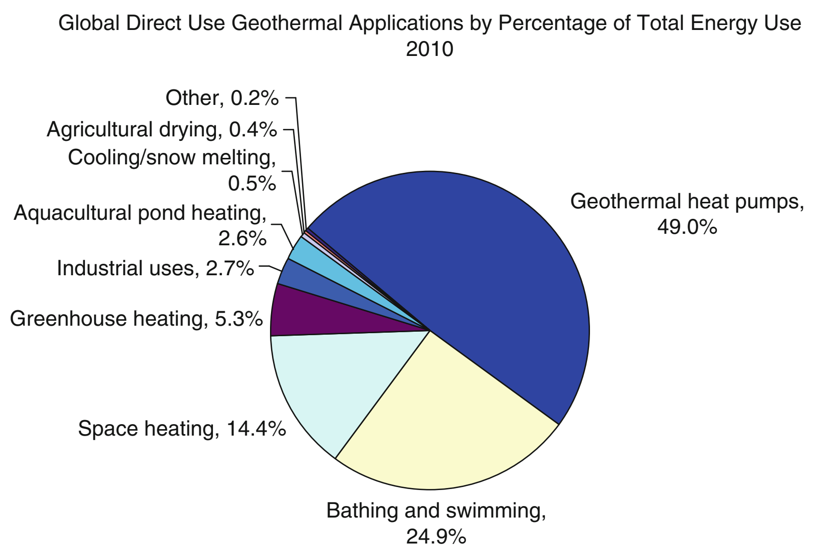
Global geothermal conditioning capacity including earth sheltering, earth tubes, and ground-based heat exchangers connected to heat pumps or other indoor conditioning equipment is not fully tracked. However, the World Geothermal Congress uses national reports to estimate the total thermal power of direct use geothermal systems. In an analysis of those reports, Lund, Freeston, and Boyd state that installed capacity increased almost sixfold between 1995 and 2010, from 8,664 to 50,583 MWt [56]. Most recent data show that approximately 49% is for conditioning with ground source heat pumps, 25% for bathing and swimming, 14.4% for direct space heating, and the remainder largely for greenhouses, aquaculture, industrial process heating, agricultural drying, space cooling, and snow melting. The annual energy savings from geothermal use based on 2010 data were equivalent to 307.8 million barrels of oil (Figs. 22 and 23).

Four countries accounted for almost 60% of the installed direct use capacity (Fig. 24): the United States (12,611 MWt), China (8,898 MWt), Sweden (4,460 MWt), and Norway (3,300 MWt). The largest increases in installed capacity between 2005 and 2010 occurred in the United Kingdom, South Korea, Ireland, Spain, and the Netherlands,

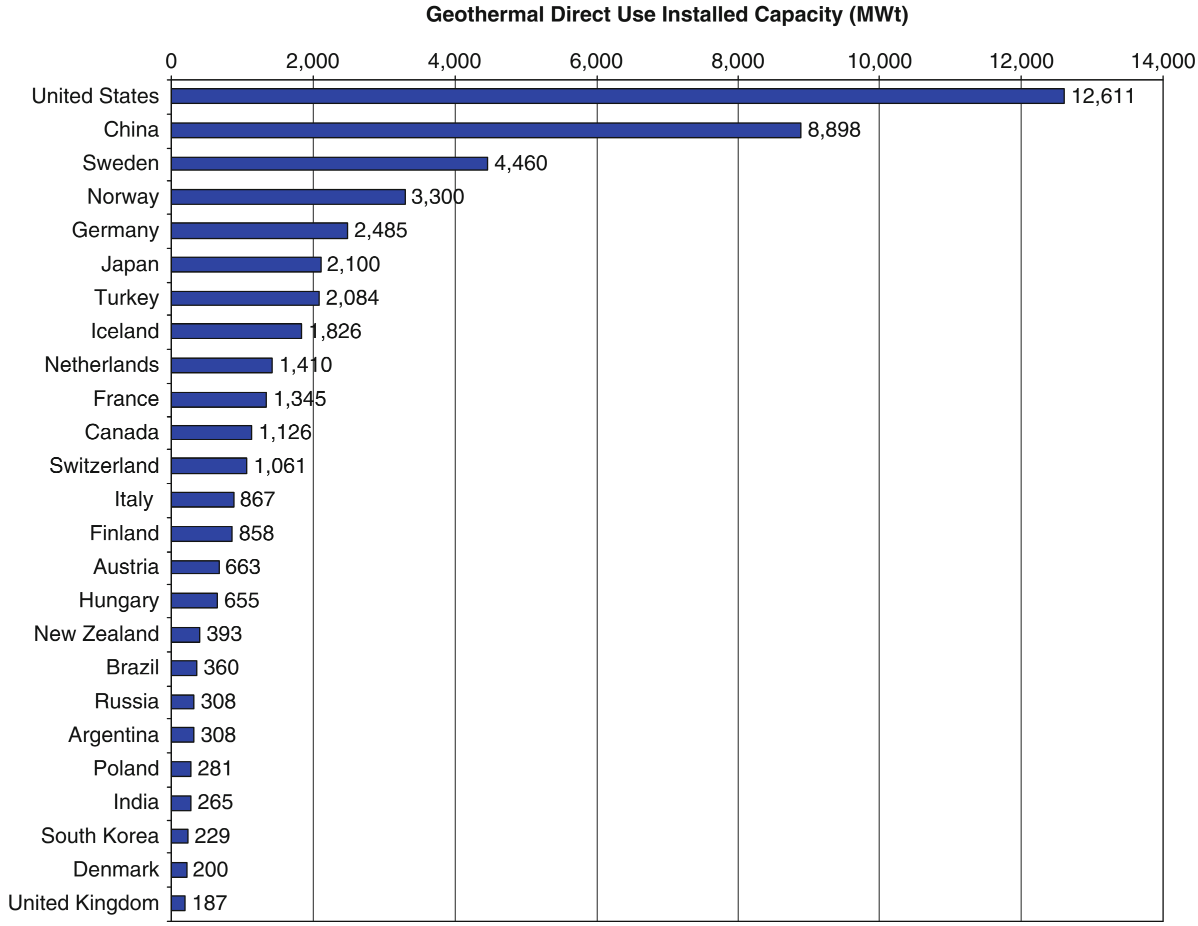


	1995 (MWt)	2000 (MWt)	2005 (MWt)	2010 (MWt)
Agricultural drying	67	74	157	127
Cooling/snow melting	115	114	371	368
Aquacultural pond heating	1,097	605	616	653
Industrial uses	544	474	484	533
Greenhouse heating	2,579	3,263	1,404	1,544
Bathing and swimming	1,085	3,957	5,401	6,689
Space heating	2,579	3,263	4,366	5,391
Other	238	137	86	41
Geothermal heat pumps	1,854	5,275	15,384	35,236

Geothermal Conditioning: Critical Sources for Sustainability. Figure 22
Global growth in installed direct use geothermal capacity



Geothermal Conditioning: Critical Sources for Sustainability. Figure 23
Global direct use geothermal application by percentage of total energy use 2010



Geothermal Conditioning: Critical Sources for Sustainability. Figure 24
Geothermal direct use installed capacity (MWt)

with heat pumps accounting for all capacity additions.

The countries with the greatest geothermal direct use energy consumption per year are China, the United States, Sweden, and Turkey, accounting for 49% of the annual total gigawatt-hours (see Table 6). When energy use per person is calculated, Iceland's geothermal direct use energy per person far exceeds all other countries (see Fig. 25). This results from the prevalence of direct use geothermal systems for space heating (such systems account for 89% of space heating in Iceland [56]) and to high energy content of Iceland's geothermal resources. "Low temperature" wells serving Reykjavik's district heating system, for example, supply water at 62–132°C [57]. Referring back to Fig. 2, the revised Lindal diagram for low-exergy conditioning, it is interesting to note that this temperature range supports cogeneration with ample residual heat for conditioning and cascaded uses such as greenhouse heating.

Future Directions

A study published by Ferguson and Woodbury in 2004 indicated that conductive heat loss from floors and basements of buildings in Winnipeg, Canada was the likely source of a regional groundwater temperature anomaly beneath the city [59]. Just as buildings and their mechanical conditioning systems can generate urban heat islands above the earth's surface, they can also alter the geothermal

Geothermal Conditioning: Critical Sources for Sustainability. Table 6 Countries with highest geothermal direct use energy per year

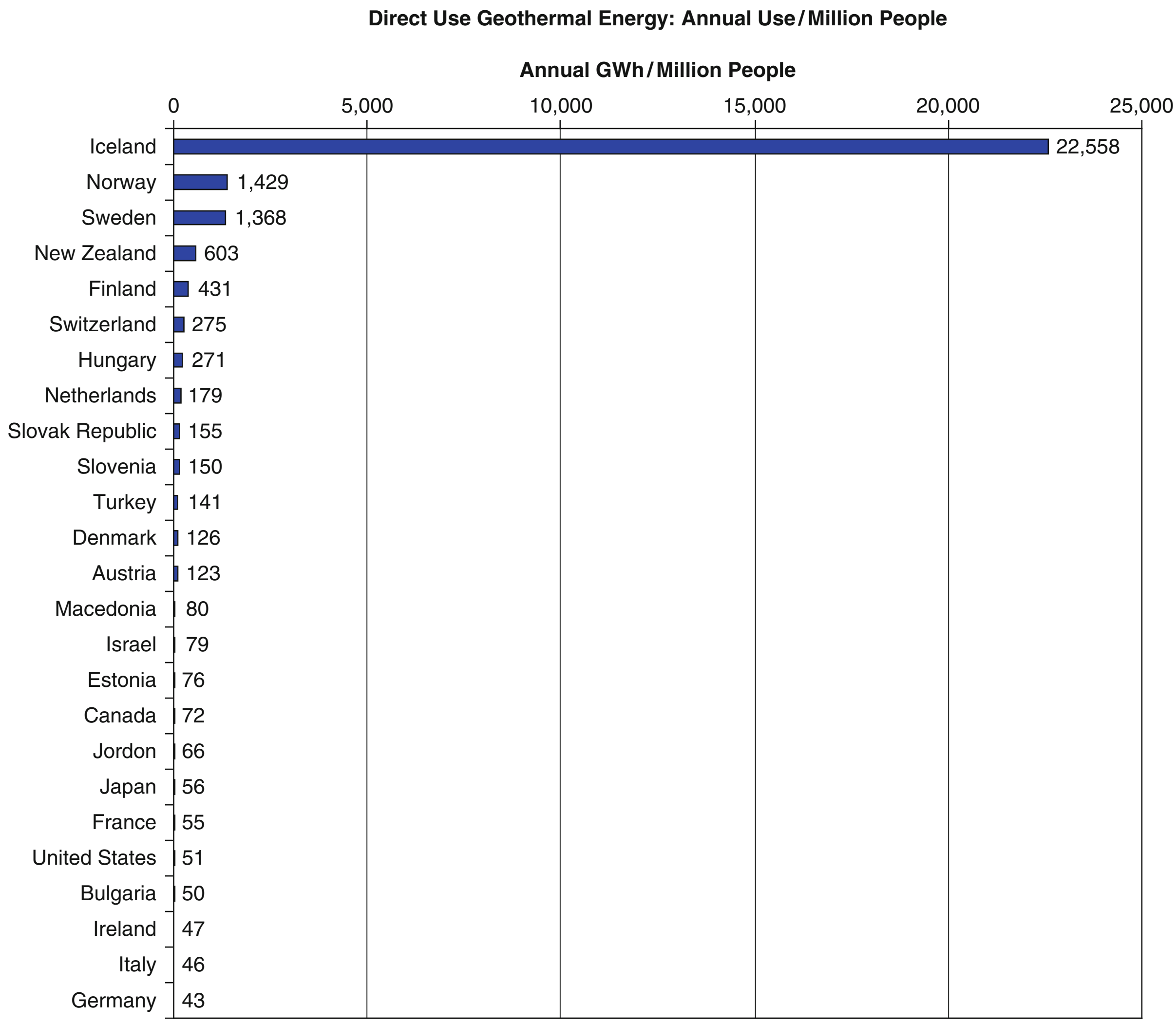
Country	Annual use (GWh/year)
China	20,932
United States	15,710
Sweden	12,585
Turkey	10,247
Japan	7,139
Norway	7,001
Iceland	6,768
France	3,592
Germany	3,546
Netherlands	2,972
Italy	2,762
Hungary	2,713
New Zealand	2,654
Canada	2,465
Finland	2,325
Switzerland	2,143
Brazil	1,840
Russia	1,707
Mexico	1,118
Argentina	1,085
Austria	1,036
Slovak Republic	852
India	707
Denmark	695
Israel	609

gradient. Fortunately, a growing emphasis on well-designed building enclosures allows heating and cooling to be provided at temperatures much closer to the human comfort range and to cut extreme heat loss or gain at the perimeter. When occupant comfort requirements can be met with low-exergy systems, building conditioning operates in a range close to the ground temperature and buildings can be coupled with the substantial thermal energy supply and storage capacity the earth offers at the building foundation. The complementary development of high-performance enclosures and geothermal conditioning infrastructure – if accompanied by ongoing monitoring and research – has the potential to appreciably reduce building energy consumption, peak demand, and corresponding carbon emissions while maintaining occupant comfort and supporting environmental health.

To some extent, further development of geothermal conditioning infrastructure is limited by issues of cost, convenience, and property ownership. Nevertheless, there are several technical advances that could further increase its use and sustainability. These developments, some of which are underway, and others that are logical extensions of trends in sustainable building design and operation, may include:

- Increased efficiency of geothermal heat pumps
- Increased use of natural refrigerants such as R-744 (carbon dioxide)
- Improved understanding and modeling of soil mechanical behavior and temperature recovery time periods for ground heat exchangers
- New sustainable approaches to bacteriological and chemical fouling in heat exchangers, piping, and associated equipment
- Improvements in the cost, size, and efficiency of ground heat exchangers
- Increased use of heat recovery from existing underground infrastructure (e.g., sewer pipe, treated wastewater pipe) for building conditioning
- Improvements in mechanical systems integration and system metering and control
- Increased use of district geothermal and solar/geothermal systems
- Development of vapor compression heat pumps powered by biogas motors or waterpower, or high-temperature gas absorption heat pumps powered by biomass [60, 61]

Expanded geothermal power production will support some of these developments since its scale provides opportunities for district systems and energy cascades. One of the key organizations that conducts and tracks geothermal conditioning research is the



Geothermal Conditioning: Critical Sources for Sustainability. Figure 25
Direct use geothermal energy: annual use/million people [58]

International Energy Agency Heat Pump Programme (IEA HPP, www.heatpumpcentre.org). Founded in 1978, HPP current member countries are Austria, Canada, Finland, France, Italy, Germany, Japan, the Netherlands, Norway, South Korea, Sweden, Switzerland, and the United States. Through its web site, news and information about member country activities are available.

The Ground-Reach Project, an international effort supported by the European Commission to evaluate the use of ground source heat pumps in meeting Kyoto targets, maintains a database of 52 GSHP projects in 15 European countries at http://www.groundreach.eu/. In the future, eight demonstration projects from Mediterranean countries and 46 case studies from European projects being field-tested through 2012 will be added to the database. A central source for accessing these case studies and other projects related to geothermal energy research and development is the European Geothermal Energy Council (EGEC) website (http://egec.info/).

Within the United States, the Geo-Heat Center at Oregon Institute of Technology, hosts an online library that emphasizes applied (how-to) engineering of direct use systems http://geoheat.oit.edu/publist.htm. With publication dates ranging from 1975 to 2008, the system details and lessons learned are particularly valuable in this library.

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Green Infrastructure and Climate Change

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Article Outline

Glossary

Adaptation (with respect to climate change) The adjusting of systems, natural or human, in response to actual or expected impacts of climate change, such as sea level rise, to reduce vulnerability or increase resilience in response to observed or expected changes in climate and associated extreme events [1, p. 869]. A distinction has been made between planned adaptation (e.g., urban planning), which is the focus of this chapter, and autonomous adaptation (e.g., by individual action such as improving housing insulation, installing air-conditioning, etc.) [2].

Ecosystem services Are "the benefits people obtain from ecosystems" [3]. "These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling" (3, Preface: V). In urban areas, ecosystem services are clearly related to land use and land cover. Therefore, spatial planning and regulations that influence the spatial pattern and intensity of land use, and in particular the provision and quality of green spaces, can have huge implications for the ecology of cities [4, 5].

Evapotranspiration The sum of evaporation of water from surfaces and the transpiration of water by plants and animals. According to US Geological Survey [6], transpiration from plants accounts for approximately 10% of air moisture. A large oak has been estimated to transpire up to 151,000 l water per year. This would account for more than 400 l/day. More modest figures are given by other sources, for example, 200 l per day for a single, fully grown beech [7]. However, generally, these figures need to be considered with great caution as they are based on rough estimates and will greatly vary between trees depending on stand and site conditions, tree condition, as well as climatic conditions.

Green infrastructure The term "Green infrastructure" was first introduced in the USA at the end of the 1990s – it has been defined as an "interconnected network of protected land and water that supports native species, maintains natural ecological processes, sustains air and water resources and contributes to the health and quality of life for America's communities and people" [8]. "Urban green infrastructure" is the network of green areas in cities. The term makes reference to other types of urban infrastructures (e.g., the road system). This interpretation of green infrastructure relates to a fine-scale urban application where hybrid infrastructures of green spaces and built systems are planned and designed to support multiple ecosystem services. It has been argued that planning of an urban green infrastructure should promote multifunctionality and connectivity of urban green space. It can integrate both public and private green space. It should be based on a long-term vision and a communicative and socially inclusive approach to its planning and management [9, 10].

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Mitigation (with respect to climate change) Reducing greenhouse gas emissions and enhancing sinks.

Resilience Is the ability of a system to adapt and adjust to changing internal or external processes [11, 12]. Resilience is the flip side of vulnerability – a resilient system or population is not sensitive to climate variability and change and has the capacity to adapt [13].

Sustainable urban drainage systems Sequence of management practices utilizing urban green areas for storage, infiltration, evaporation, and conveyance of stormwater runoff.

Urban heat-island effect Significantly higher temperatures experienced in cities compared to the rural surroundings as a result of changed solar reflection in the built environment, less evapotranspiration, and anthropogenic heat from combustion engines, heating of buildings, and other use of energy.

Vulnerability (with respect to climate change) Is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity [1, p. 883].

Definition of the Subject

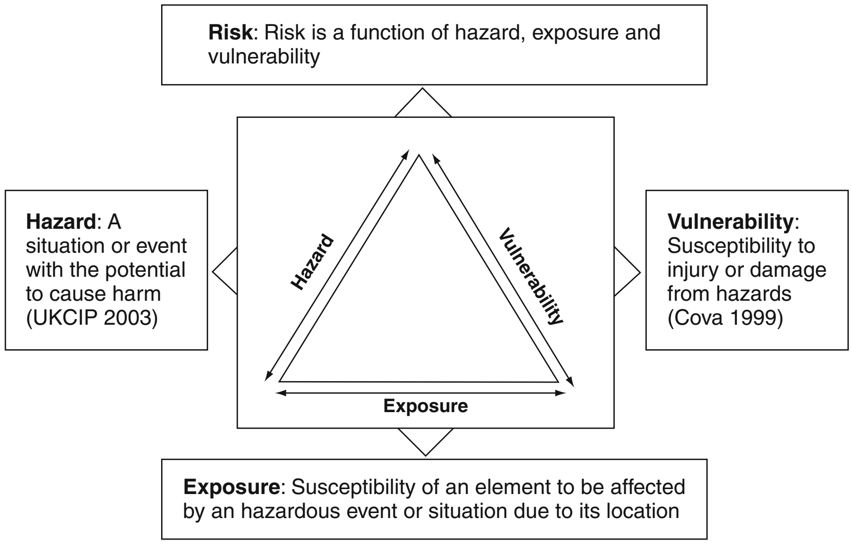
By 2050, two-thirds of the world's population will live in cities. Already today, cities of the developed world are a major source of greenhouse gas emissions. Therefore, cities need to make serious efforts to mitigate climate change. Urban planning can play a major role in this respect by designing compact, low footprint cities. However, climate change will also make a severe impact on cities mostly by intensification of the heat-island effect, increase of surface runoff from more frequent and intense rainstorms, and by coastal and riverine flooding. Urban planning will play an important role for development and implementation of integrated strategies for climate change mitigation and adaptation. Notably, "green infrastructure" can assist in adapting cities to climate change by reducing the urban heat-island effect and by managing stormwater runoff. Urban greening, such as planting of shade trees and roof greening, can also reduce the energy demand for house heating and cooling. Therefore, the design of the urban landscape will have a direct influence on mitigating climate change and the impact of climate change on people's livelihoods and assets.

Introduction

Urbanization and climate change are closely related. At present, more than half of the world's population lives in cities. Over the next 40 years, the world's urban population is projected to increase by more than three billion people [14]. This will almost double the current urban population and lead to massive land-use changes in and around current urban settlements.

The urban built-up areas are expected to increase by 250% and cover about one million square kilometers by 2030 [15]. This corresponds to the development of more than four hectares of new urban land every minute in the next 20 years. Ninety percent of the future urban expansion is expected to take place in Asia and Africa [14]. New urbanization is primarily an issue in developing countries whereas already 70–90% of the population of the developed world lives in urban settlements. Therefore, climate change mitigation and adaptation is an equally important issue in the developed as well as the developing world.

It has been estimated that 78% of carbon emissions from fossil fuel burning and cement manufacturing [16] and 85% of the anthropogenic emissions of carbon dioxide, chlorine-fluorine-carbons, and tropospheric ozone stem from urban areas [17]. While these and similar figures have been debated [18], there can be little doubt that urban areas, particularly in the developed world and in the transition countries, need to play a major role in climate change mitigation. According to recent reviews, this message has come through as the abatement of greenhouse gas emissions is rising on the political agenda of many cities, particularly in the developed world [19, 20]. Greenhouse gas emissions can be reduced in many different ways by all sectors and at all levels of organization of human society. The overall urban form also plays a role. The "compact city" model has gained wide acceptance as a way to achieve more resource-efficient cities. It is based on the notion that urban density is related to energy consumption, as denser cities consume less



Green Infrastructure and Climate Change. Figure 1
Illustration of risk as a function of hazard, exposure, and vulnerability [26] (Adapted from [26] by [116] with permission from author)

energy per capita. This applies especially for car-based travel [21]. This relationship has been used as a powerful argument against urban sprawl, that is, the extension of urban areas through low-density developments. For instance, European cities have on average expanded by 78% in area since the mid-1950s while their population increased by only 33% [22]. Large urban regions have developed, which spread far into the previous countryside and can be delimited by patterns of daily commuting [23]. Sprawl has even been observed in city regions with a decreasing population where people move out from declining inner cities to live in fringe locations [24].

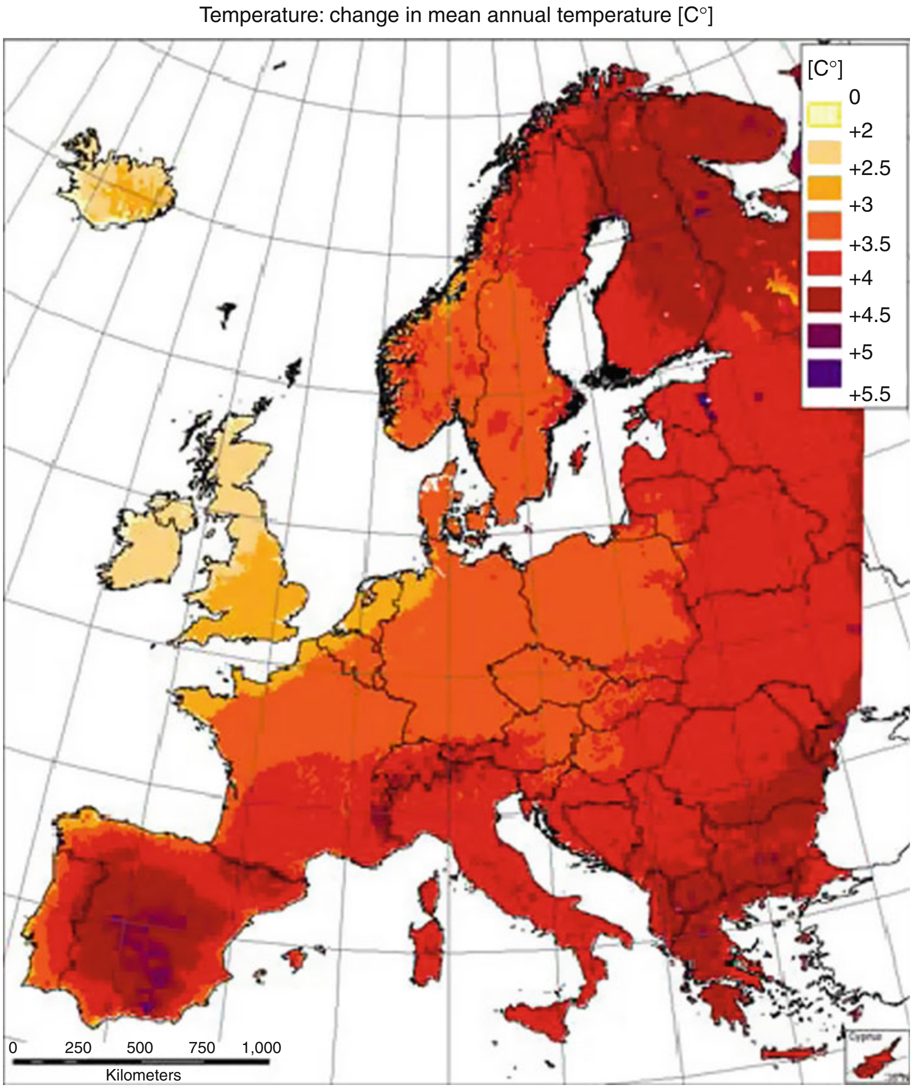
While city governments rightly have given much and still-increasing attention to reducing greenhouse gas emissions, adaptation to climate change has been of much less concern until recently (see reviews in [19, 20, 25]). Moreover, activities are still mostly focusing on certain sectors such as increasing the capacity of the water supply and the sewer systems.

Following Crichton [26] (Fig. 1), the climate change-related risks of urban areas are a function of the (1) hazards, (2) exposure of the urban system to these hazards, and (3) its inherent vulnerability:

1. *Hazards*: By 2100, the average global surface temperatures are projected to rise by 1.1–6.4°C and the sea level is expected to rise by 0.18–0.59 m. Annual precipitation levels will increase in high latitudes and decrease in most subtropical land regions. Hot extremes, heat waves, and heavy rain events are expected to increase, while storms and cyclones will intensify [1]. Regions most vulnerable and/or exposed to climate change include the Arctic (high rate of warming), Africa (low adaptive capacity), small islands (exposure to sea level rise and storms), and the Asian and African "megadeltas" (dense populations combined with exposure to sea level rise, storm surges, and river flooding). Overall, three effects of climate change are of particular concern for urban areas:

– Sea level rise and increase of storm surges caused by tropical storms
– Temperature rise, which intensifies the urban heat island
– Changing amounts and patterns of precipitation, which increase the risk of drought, on the one hand, and pluvial and sewer flooding and landslides from rainstorms, on the other hand

Taking Europe as an example (Fig. 2), temperatures will increase in particular in the North and the South but in more moderate ways in Central and North West Europe. In the North, temperatures and precipitation



Green Infrastructure and Climate Change. Figure 2
IPCC scenario A2 for Europe [117]. Absolute change in mean annual temperature between control periods 1961–1990 and 2071–2100, under the IPCC SRES scenario A2. The maps are based on PRUDENCE data (http://prudence.dmi.dk), and processed by the European Commission's Joint Research Centre, Institute for Prospective Technological Studies, within the PESETA study (http://peseta.jrc.es). ©European Union, http://eur-lex.europa.eu/

will particularly rise in wintertime, while the South will be affected by hotter and drier summers. Not all of these changes will be negative to living in the city. For instance, human winter mortality and heating demands are expected to decrease in northerly areas. Also, the summer half year will become more beneficial for outdoor activities in the north. Yet, even for countries such as Sweden, it has been estimated that these beneficial effects are outweighed by increased mortality due to heat waves and increased energy demands for cooling during summertime [27]. In particular, it needs to be highlighted that it is less the general change of temperature and precipitation patterns that are of concern but the increasing frequency and intensity of extreme events such as hot spells of weather and droughts, more frequent thunderstorms that bring large quantities of rainfall in a short time, and perhaps also a higher likelihood of heavy storms, although this is far less certain. For instance, it has been predicted that the number of so-called tropical nights will rise. Tropical nights are nights where the air temperature does not drop below 20°C. Under the IPCC scenario A2, it is predicted that the night temperatures in central Europe in 2080 will be similar to current levels in Spain [28].

2. *Exposure*: Urban areas are often located in zones particularly exposed to climate change hazards such as storm surges, river floods, and landslides. As an example, 13% of the world's urban population live in the low-elevation coastal zone (<10 m above sea level) [29]. Almost two-thirds of urban settlements with a population greater than five million are located in this zone, including the densely populated deltas of Ganges-Brahmaputra (Kolkata, Dhaka), the Nile (Cairo), and the Yangtze River (Shanghai). These areas are at particular risk from flooding when high tides combine with storm surge and/or higher river flows. Yet, not all areas within coastal cities are equally at risk. In a developing world context, particularly the informal settlements of the urban poor are exposed to flooding.

3. *Vulnerability*: Urban vulnerability to climate change is multifaceted and related to the physical, social, economic, and environmental characteristics of urban areas. Various concepts of vulnerability have been proposed by the research community on climate change and disasters [30, 31]. The emphasis is thereby either placed on vulnerability, mainly as a result of physical factors, for example, location and layout of the city ("outcome vulnerability") or of its social makeup, that is, the condition of people that enables a hazard to become a disaster ("context vulnerability"). Adoption of either one of the concepts has consequences for the measures to be taken to reduce urban vulnerability.

An obvious reason for the vulnerability of urban areas to climate change is the concentration of people, infrastructures, and economy. Further, the urbanization process per se increases the vulnerability. Urbanization fundamentally alters the earth's surface by replacing vegetated or otherwise open land with built land, and urban areas may be characterized as open ecological systems with a high throughput of energy and matter. Consequently, ecosystem processes are strongly impacted, such as modification of local and regional climates, air quality, hydrology, soils, and flora and fauna [32]. Annual average air temperatures in big cities are already 1–3°C higher than in the surrounding countryside. Thus, already today, climatic conditions in urban areas may correspond to anticipated climate change. However, urban areas' climate will be further modified by climate change and stormwater runoff will strongly increase [25].

Planning: The critical role of land-use planning and management in climate change mitigation and adaptation has been recognized by the Intergovernmental Panel for Climate Change [1].

Urban planning and land management can mitigate the severity of hazards and reduce the levels of exposure and vulnerability [33]. Land-use planning can reduce transport demands and building regulations can reduce the need for house heating or cooling [20]. Directing urban development away from floodplains can greatly reduce the risks of being affected by increasingly frequent and severe floods. As will be argued in the following sections, planning can increase the resilience or capacity of urban areas to cope with climate change by strategic planning of a green infrastructure. As Lindley et al. observe, "different scales of planning from macro-scale land-use planning to micro scale urban design are both important to this process, responding to the different scales over which risk and vulnerability are expressed" [33, 34]. Integration of climate change-induced risks in urban planning is, however, only beginning to emerge [35, 36].

Urban areas are densely built, densely populated, have high land costs, and must support multiple functions. This calls for innovative solutions to the design of urban areas that are inclusive and synergetic. It is a challenge that can, at least partly, be addressed by transferring landscape design principles into the design of the city.

There is ample evidence of the beneficial role of urban green space in providing ecosystem services [37–39]. Green space can mitigate the urban heat-island effect and reduce stormwater runoff [40, 41]. Trees and shrubs also sequester carbon, and if the amount of living biomass in a city is permanently enlarged, the overall carbon balance of urban areas will be improved [42]; however, the contribution is likely to be only of marginal importance. The question that remains to be answered is to what extent cities can adapt to the expected large alterations of the environment driven by climate change through planning and design of an urban green infrastructure? Green infrastructure is an emerging concept increasingly gaining acceptance in the fields of urban planning and design as a way to promote multiple ecological and cultural processes in the city [9, 10]. Infrastructures facilitate multiple functions in the city including transportation, communication, energy, and water services. Most existing infrastructures are "grey infrastructures" such as roads and sewers. The "green infrastructure" complements these infrastructures by providing essential ecosystem services such as climate regulation, stormwater management, biodiversity, and social services such as recreation and aesthetics [9, 10]. Has green infrastructure, similar to other infrastructures such as transport and supply infrastructures, the ability to maintain the viability of the city as such by the provision of ecosystem services and increased resilience [10]?

The Role of Green Infrastructure for Adaptation of Cities to Climate Change

Adaptation of cities to climate change refers to the implementation of means to reduce the impact of climate change. By timely preparing the city to face the impact of a changing climate, economic and social costs and potential damage costs can be reduced while synergies can be realized, for instance by developing more attractive and livable cities [43]. Development of the green infrastructure is an effective strategy both for adaptation to and mitigation of climate change.

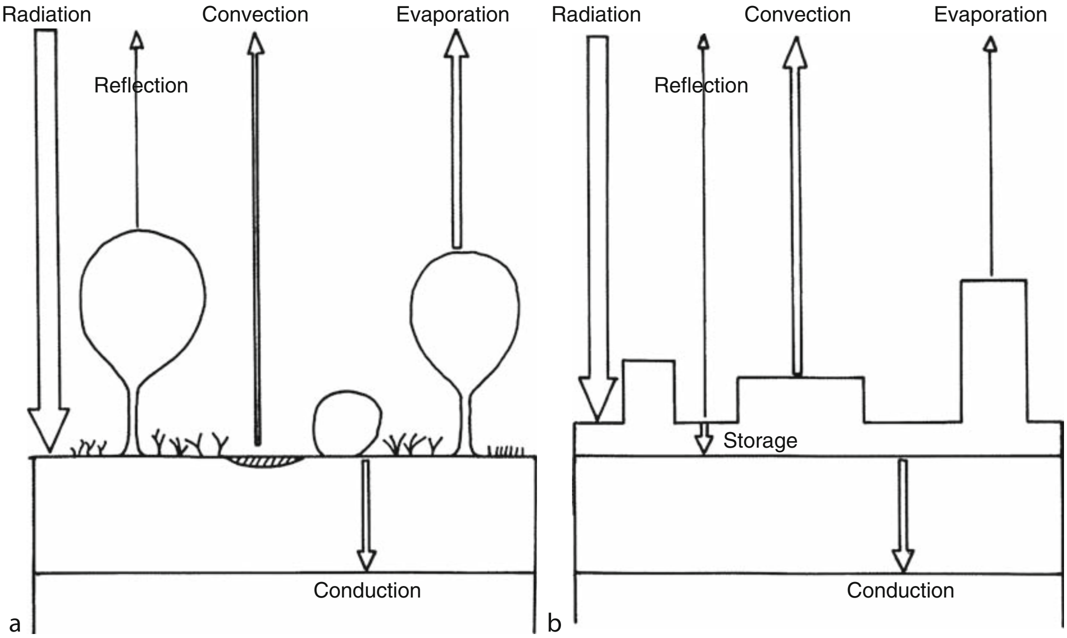
Adaptation to Rising Temperatures – The Heat-Island Effect

The local climate in urban areas differs from the surrounding open land [44]. Of particular relevance in the context of climate change is the increase of air temperatures in urban areas by 1–3°C on annual average compared to the surrounding open land. On warm summer days, the difference can be up to 5–12°C [45]. This is commonly referred to as the urban heat-island effect. The intensity of the heat-island effect is dependent on the size of the city: the larger the city the stronger the heat-island effect. This is relevant as many urban areas in the world are strongly growing, and the resulting increase of air temperatures in inner cities may be stronger than that caused by global climate change. However, climate change is expected to further intensify the heat-island effect. For instance, a modeling study predicted intensification of the heat-island effect for London by 0.5°C by the 2050s [25].

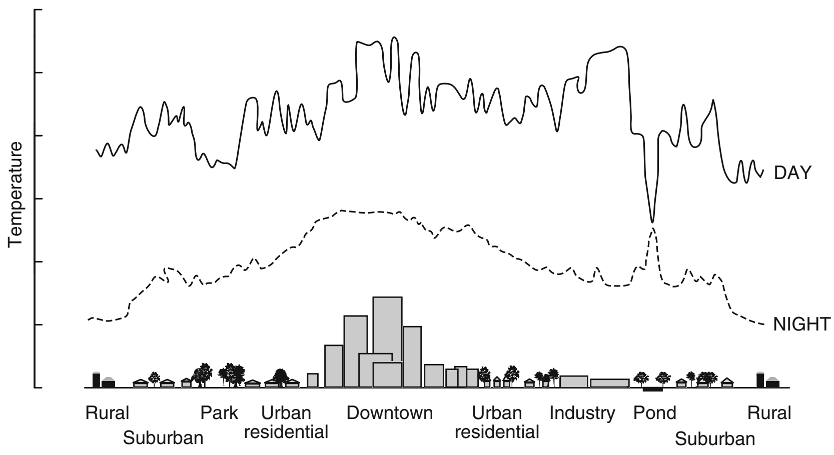
In warmer cities, it will be more difficult to work and sleep properly without cooling and ventilation systems. This will increase energy demands; it will cost money and cooling systems are only available to people who can afford it. In the USA, peak urban electric demands were estimated to rise by 2–4% for each 1°C rise in daily maximum temperature. The additional use of air-conditioning is responsible for 5–10% of urban peak electric demand in the USA, at a direct cost of several billion dollars annually [46].

Increased temperatures in urban areas can have negative consequences for human health and well-being. In particular, small children and elderly people as well as persons suffering from cardiovascular diseases are at risk from hot spells of weather. An example is the extreme summer of 2003 in Europe where more than 70,000 deaths in excess have been reported [47]. Most casualties occurred in urban areas where most people live and the heat-island effect intensifies. As outlined above, such hot summers with extreme heat waves will become more frequent and intense in the future [28]. In addition to direct impacts through raised temperatures, the heat-island effect also deteriorates air quality. For instance, the heat-island effect in Los Angeles, California, has been estimated to increase ozone concentrations by 10−15 [48]. It should be noted, however, that climate change impacts on urban areas will play out very differently according to location and type of city and a decline of winter mortality can be expected in urban areas in colder climates.

The heat-island effect is a result of the altered climatic balance in urban areas and it is caused by a number of factors, such as the reflection, storage, and convection of solar energy and emission of heat from anthropogenic process (Fig. 3, [41, 45, 49, 50]). The main reason, however, is the replacement of vegetated, evaporating surfaces by built and paved surfaces. Vegetation consumes much of the solar energy for evaporating water. This imbalance is fortified by the fact that buildings, roads, and pavements are made of



Green Infrastructure and Climate Change. Figure 3
Energy transfers contributing to the urban heat-island effect: (**a**) the situation in the open land, (**b**) the situation in densely built-up areas [40] (Reprinted from [40]. Copyright (2001), with permission from Elsevier)



Green Infrastructure and Climate Change. Figure 4
Variations of surface temperatures in urban transect. (Modified from [118] with permission from Actionbioscience.org the author)

materials with a higher capacity to accumulate and store heat than living tissues. Measurements show surface temperatures do not decrease continuously along urban to rural transects but vary strongly within the urban area depending on the physical characteristics of the different land uses along this gradient (Fig. 4). Temperature peaks can be observed in densely built parts of the city, while temperatures are considerably lower in well-greened areas. Therefore, there is not one heat island but in reality a city consists of a small-scale archipelago of heat and cool islands which corresponds well to patterns of urban form.

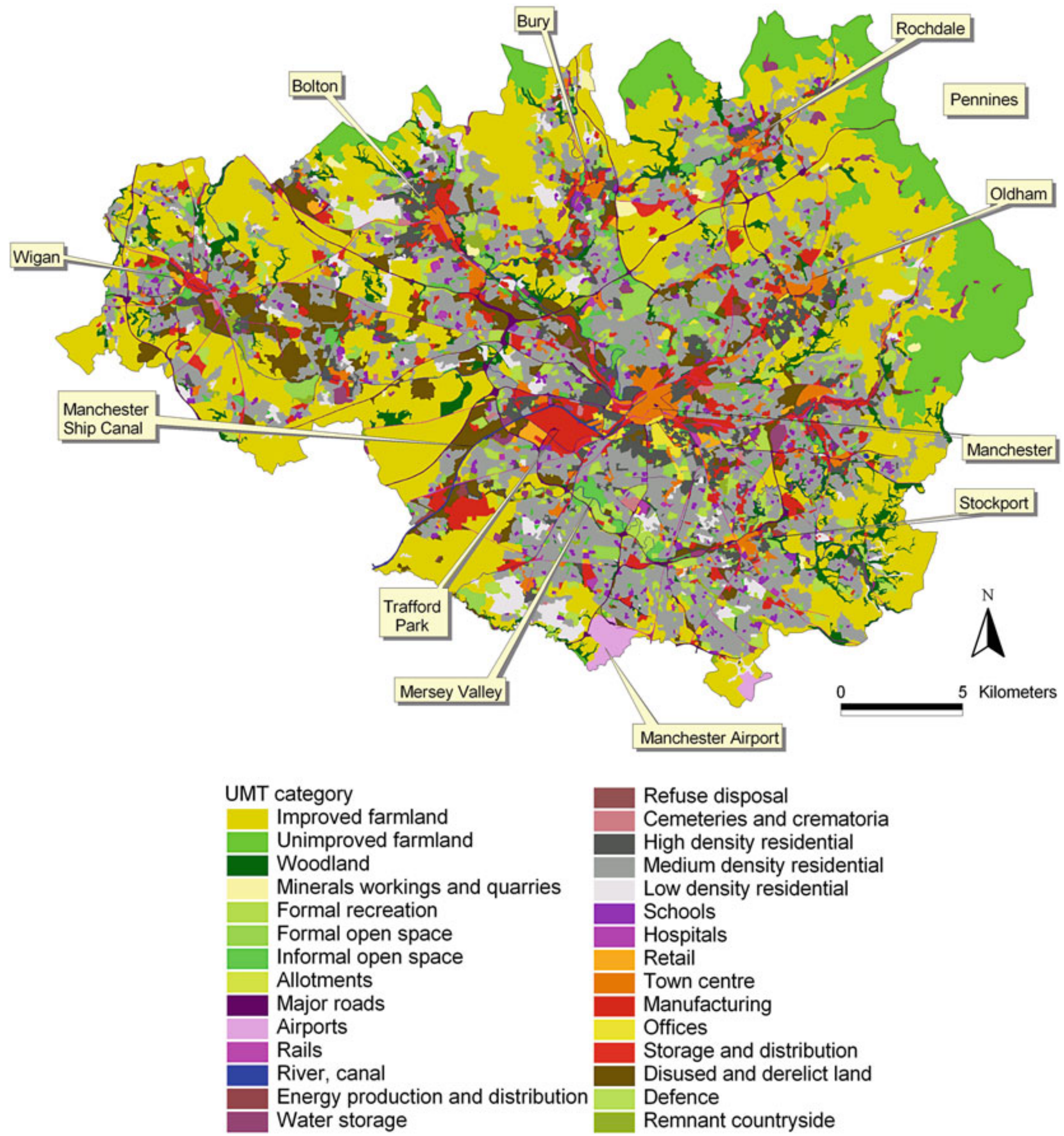
Although air and surface temperatures can be lower in green spaces than in the surrounding built areas, the effect varies depending not only on the location, size, and design of the green space but also their management (e.g., whether lawns are irrigated). In a large park, annual average air temperatures may be 1–2°C lower than the surroundings. During clear windless nights, temperature differences can be as big as 5–6°C. Moreover, heat is trapped in narrow street canyons of densely built areas. However, parks must have a certain size to develop a distinct climate. According to measurements in public green spaces in Berlin, temperature differences could only be found when the park was bigger than approximately 3.5 ha [51].

Larger parks can also moderate air temperatures in adjacent built areas. The study on green spaces in Berlin (Germany) established that very large parks such as Tiergarten (212 ha) can lower air temperatures on clear summer days with low wind speeds (<2 m/s) up to 1,300 in lee and up to 200 m windward [51]. Yet, while these figures may be impressive, the effect is much less for smaller green spaces where effects may be limited to distances of 100–200 m. The cooling effect also depends on the surrounding built structures. Corridors in the main wind direction may lead cool air from the park into adjacent built areas whereas closed built structures around the park block the cool air [52]. Therefore, mitigation of the urban heat island cannot rely on single large green spaces. Instead, a dense network of green spaces should permeate the built fabric. Moreover, greening of the urban matrix is crucial to provide for comfortable climatic conditions close to where people live and work. Air temperatures clearly differ between urban land uses dependent on the degree of greening. Even in very densely built areas, shade trees can be planted in streets to control climates at site levels while roof and wall greening reduce the heating up of built surfaces and heat storage. Trees are particularly effective in cooling the city as they have a shading effect. Therefore, parks with a high provision of trees and urban forests are usually the coolest outdoor areas during daytime.

While there is ample evidence from urban climate studies to establish the relationships between urban form, green space, and climates at various scales – from city to streets – research on the likely consequences of climate change on urban climates and the potential of green infrastructure to mitigate these effects are still scarce. One of the few exceptions is a study undertaken in Greater Manchester, UK. In the project "Adaptation Strategies for Climate Change in the Urban Environment" (ASCCUE) [53, 54], a modeling approach was employed to explore the impacts of climate change on urban temperature patterns and establish the relationships with urban form. In Greater Manchester, a large conurbation of approximately 2.5 million inhabitants on a surface area of approximately 1,300 km^2 was selected as it suitably represents the different forms of built and open spaces that are typical for large urban areas in the UK. Greater Manchester is also an interesting case as it undergoes a rapid process of transformation from a former industrial to a postindustrial city where land-use dynamics are high. It also offers opportunities for development of a green infrastructure for climate change mitigation and adaptation.

In the ASCCUE project, the researchers developed an approach for the assessment of climate-related risks with reference to three exposure units: built, green space, and human comfort. However, only the results from research on urban green space will be reported. This study consisted of three main steps:

1. Characterization of the urban environment based on mapping of urban morphology types from aerial photographs [55]: Overall, the area was classified into 29 "urban morphology types" (Fig. 5). These were further characterized by nine land cover attributes, including cover of built, paved, and vegetated areas by interpretation of aerial photographs. For the latter, detailed estimates were derived for trees, shrubs, rough grasslands, lawns, and arable land.
2. Modeling surface temperatures (and stormwater runoff, which will not be reported here) based on an energy exchange model [40, 54]: Surface temperatures are a useful climate indicator for urban planning as information can be derived from remote sensed imagery or – as was the case here – from models with complete spatial, highly resolved coverage of urban areas whereas measurement of air temperatures is confined to point data or transects from where it is difficult to spatially



Green Infrastructure and Climate Change. Figure 5

Map of Greater Manchester divided into 29 urban morphology types (Reprinted from [55]. Copyright 2008, with permission from Elsevier) extrapolate. Moreover, surface temperatures can be taken as a proxy for mean radiant temperatures, which have a strong influence on human comfort and health in outdoor environments, especially on hot days with little wind [56]. For instance, impacts of the heat waves in 2003 in Paris showed that increased levels of human mortality were closely related to heat islands of surface temperature derived from remote sensed data [57]. In the Manchester study, the surface temperature model's main input were land cover data, on the one hand, and climate data from the local weather station, on the other. Climate data were obtained from a parallel project, where climate scenarios were derived for the weather station of Manchester airport for 2020, 2050, and the 2080s [58, 59]. Only results for the most extreme emissions scenario called "2080 high" will be reported here.

3. Urban development scenarios to compare the impacts of "green" versus "densification" strategies under climate change until 2080: In the green strategy, cover of vegetated and water surfaces would be increased by 10% in terms of surface cover while the densification strategy would lead to a reduction in cover of evapotranspiring surfaces by 10%.

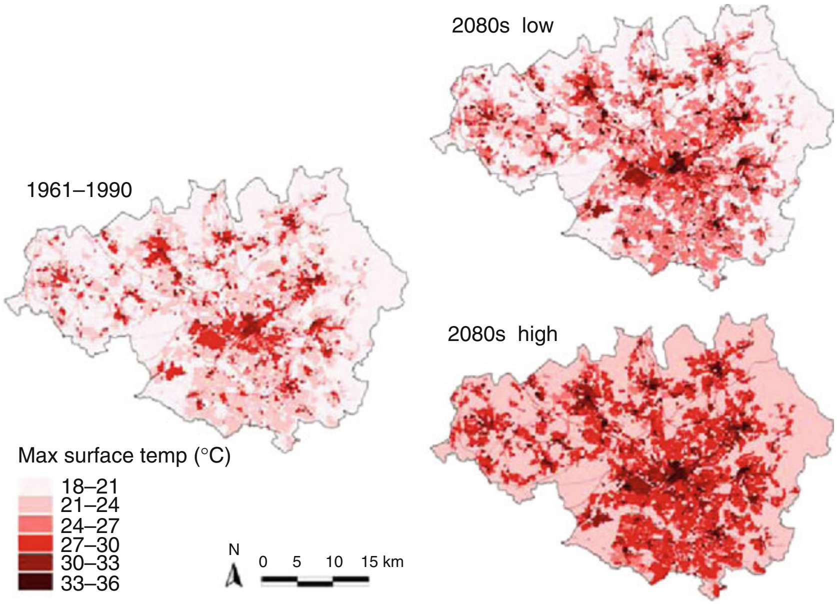
The share of green space varies between urban morphology types. In the inner urban areas, the share of green space is usually low (less than 20%); in single-family housing estates, the provision of green space is 50–60%. Overall, formal and informal green spaces (including woodlands) cover approximately 10% of the city surface; another 10% is covered by vegetated areas on derelict land of former industrial sites. Yet the largest green space resources are residential areas where approximately 40% of all vegetated areas can be found. Large differences, however, could be observed between densely built-up residential areas (e.g., terraced houses), and the medium- and low-density types. These differences generally coincide well with the socioeconomic status of the areas with deprived areas being at the lower end of green space provision. Moreover, they often lack in mature trees with large crowns, which are particularly effective in reducing surface and air temperatures via their shading effect.

Surface temperatures greatly differ between the urban morphology types on hot summer days, and these differences are clearly related to the cover of green space (Fig. 6). The highest surface temperatures were identified in the inner city, where buildings, roads, and pavements predominate and where the provision of parks, trees, and other types of vegetation is lowest. Temperatures were also very high in densely built residential areas and industrial and commercial estates. In well-greened neighborhoods with single-family houses, the temperature is considerably lower, whereas woodlands offered the coolest places. The study measured 32.1°C in the urban center, while the temperature in a large park was only 18.4°C.

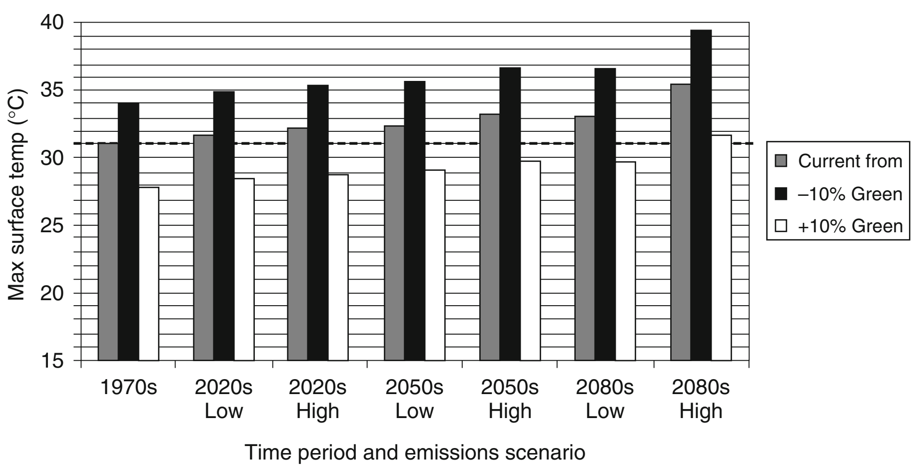
In the Manchester study, climate scenarios for the year 2080 predicted a rise of air temperatures of more than 4°C during heat waves. The rise in temperature is significantly lower in areas with a high provision of green spaces. While surface temperatures would increase by 4.3°C in the city centers, they would only rise by 3.1°C in low-density residential areas. This shows that the cover of vegetated areas has potential to buffer the effects of climate change to some degree. These results compare favorably with the predicted intensification of the heat island in London mentioned before [25].

The climate scenarios for 2080: the "green strategy," where the provision of green space in the densely built town centers was increased by 10%, and the "grey strategy," where the provision of green space was reduced by 10%, resulted in further support for the important role of green space to increase the coping capacity of urban areas to climate change. It was estimated that 10% more green space would almost compensate for the rising temperatures expected to result from global warming by 2080 even in the worst scenario. In contrast, by reducing the provision of vegetated areas by 10%, the temperature in dense urban areas would rise by 8.2°C (Fig. 7).

It will be very challenging, though, to introduce more green space into densely built urban centers. However, the dynamics of urban areas should not be underestimated: current uses become obsolete, buildings are demolished, and entire neighborhoods are renewed. This may give opportunities for development of a green infrastructure if strategies are clearly defined and supportive to the wider agenda of urban renewal. In particular, this may be feasible in cities with a shrinking population [24] where creation of green spaces can also increase quality of life and thus help to

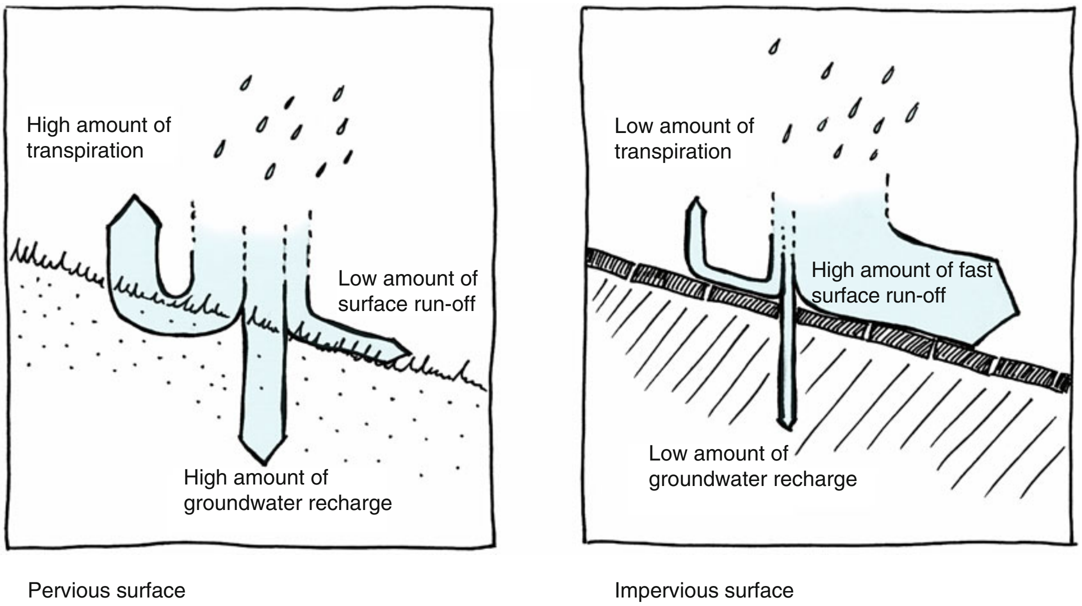


Green Infrastructure and Climate Change. Figure 6
Maximum surface temperatures in Greater Manchester on a hot summer day in 1961–1990 and the 2080s low- and high-emission scenarios [54] (Reprinted from [54]. Copyright (2007), with permission from Alexandrine Press)



Green Infrastructure and Climate Change. Figure 7
Maximum surface temperature for a hot summer day in inner city areas of Manchester, with current form and when 10% green cover is added or removed [54] (Reprinted from [54]. Copyright (2007), with permission from Alexandrine Press)

reverse the tendency of decline. In the city of Leipzig, the potential of developing urban woodlands on derelict inner urban sites is currently explored [60]. The project revealed that overall there are more than 500 sites within the built area covering over 1,100 ha. Many sites are located in deprived areas where there is a lack of green space and environmental quality is poor. Therefore, these derelict areas offer a great potential to improve quality of life in these areas. Moreover, they would allow developing a network of strategically placed "cool islands" in otherwise still densely built areas for climate change adaptation.



Green Infrastructure and Climate Change. Figure 8
The water cycle in natural and sealed areas. (Adapted after [119] with permission from the author)

Where pressure on the land is high, and urban densification rather than urban sprawl is sought, it may be more difficult to develop a green infrastructure and other strategies need to be adopted. Even there, opportunities may exist. For instance, in the city centers of Manchester, about 37% of the city is covered by buildings but 40% by paved spaces of roads, car parks, etc. Thus, it is not the lack of space as such but the intensive use and in particular the occupation by car-based transport which is problematic. Evidently, it is difficult to change this situation but adaptation to climate change will require more radical measures to be taken for the reorganization of transport in city centers in order to create the space necessary for green space. Here, synergies with climate mitigation are obvious. In addition, green roofs and walls or implementing vegetated permeable pavements should be promoted.

Stormwater Management – From Sewer-Based to Landscape-Based Systems

The ongoing sealing of surfaces due to buildings, roads, and other infrastructure in urban areas leads to a change in the water cycle (Fig. 8). Instead of naturally high transpiration rates and water infiltration for groundwater recharge, large amounts of the precipitation become surface runoff. In natural environments, about 10% of precipitation will run off on the surface and 50% infiltrate, whereas figures are reversed in dense urban settings with about 50% surface runoff and 10% infiltration – of course very much dependent on the specific degree of surface sealing [4]. This leads to a higher and more rapid peak discharge in urban areas, which needs to be handled by the existing sewer systems.

Due to fast urban development and the aging of the systems, already today many existing sewer systems have insufficient capacity. Increase of water-impervious surfaces has been dramatic in urban areas of the Western world. For instance, a study of 26 cities across Europe revealed that the size of urban areas increased by 78% on average between 1950 and 1990 while population increased only by 33% [22]. This low-density development has greatly enlarged the area of water-impervious surfaces for buildings and roads. In addition, densification of existing built areas increases the amount of water-impervious surfaces. Such densification may take different forms, from building over derelict or other non-built areas, infill development, for example, by building houses on vacant land or subdividing large gardens into several smaller parcels. Paving of front gardens to create parking spaces can lead to significant increase of water-impervious surfaces. Research in 11 residential areas in the Liverpool conurbation revealed that approximately 5% of the surface area was converted from vegetated to paved, between 1975 and 2000. The runoff from a 10 mm rainstorm event was modeled to increase on average by 4% [61]. While these changes may appear to be small, they can lead to significant problems for the sewage system when accumulated over an entire sewer catchment. In another UK-based study, increase of water-impervious surfaces due to conversion of front gardens was even bigger: A 13% increase in water-impervious surfaces was detected in a 1.16 km^2 suburban area of Leeds in northern England over the 33-year study period between 1971 and 2004 [62]. An increase of stormwater runoff by 12% was modeled as a consequence.

The increase of stormwater runoff leads more and more often to sewer overflows. This can either be uncontrolled, resulting in the flooding of urban areas, or the overflow happens controlled into nearby streams and other receiving water bodies. In this case, the ecological consequences can be dramatic.

Climate change will strongly exacerbate these problems. In the Manchester study, it was predicted that the amount of precipitation from rainstorm events will increase by 56% until 2080 in the high-emissions scenario. This would lead to 82% more runoff because of limited water retention and infiltration capacity of the soils [54]. Protection of green space on soils with a high infiltration capacity such as sandy soils will be a major task for urban planning to avoid a further dramatic deterioration of this situation. An increase of green space cover by 10% – as explored in the case of heat-island mitigation above – would reduce surface runoff during a rainstorm event by approximately 4%, and thus not suffice to solve the problem. However, implementing on-site retention and infiltration techniques can be a way out, as will be explored in the following section.

The northern European country Denmark will be taken as an example. Comparing regional precipitation data from 1979 to 1997 with 1997–2005 suggests a 10% increase in rain intensity for a 10-year design storm [63]. Model simulations project that extreme rain events will further increase by 20% or more during the next 100 years [64]. To comply with more intensive rainstorms, the drainage capacity needs to be increased by approximately 30% in a 100-year time perspective [65]. Including uncertainties related to urban drainage modeling and urban densification processes, the expansion of drainage capacity is estimated to be 78% higher than present level [65]. This is only to maintain the same flood risk as today, that is, surcharge accepted every tenth year in combined sewers collecting stormwater runoff and wastewater from households and industries in the same pipe system. For the country as a whole, the cost of increasing drainage capacity by conventional means (i.e., installing bigger and more sewers, basins, and pumps) is estimated to be $2.7 billion USD in a 30-year time perspective [66]. Combined with sewer rehabilitation works resulting from aging infrastructures, the total cost accounts to $14.6 billion USD [66]. With a total urban population of 4.5 million people, this corresponds to investment needs in the range of $3200USD per urban capita. Still, there is no certainty that the predicted level of climate changes are reliable and that the one-off investments in new pipes (relying on long depreciation periods) will provide sufficient drainage capacity in the future. If no action is taken, the risk of floods will increase, which will impact people's assets and livelihoods.

Large challenges lie ahead in adapting cities to more extreme rain events. Conventional solutions are costly and possibly unsustainable long term [67, 68]. Another solution is to imitate the natural water cycle with delay, infiltration, or evaporation of the stormwater as close to where it falls as possible. Single measures for such on-site stormwater management are elements like green roofs, permeable pavement, swales, ponds, and infiltration trenches. This strategy is also referred to as landscape-based stormwater management, Sustainable Drainage Systems or Sustainable Urban Drainage Systems (SUDS), Best Management Practices for Stormwater (BMPs), Low Impact Development (LID), or Water Sensitive Urban Design (WSUD) [69, 70].

Sustainable urban drainage systems (SUDS) can be used as a full stand-alone solution typically employed in new urban developments or retrofitted into the existing city to provide more drainage capacity in the area, in which case it is more likely to be complementary to the existing sewer system. SUDS further provide the opportunity for comprehensive solutions to suspend recreational and spatial utilization of the water as well as increased biological diversity and well-functioning urban drainage systems that contribute to increased groundwater recharge. This type of solution is expected to include economical, environmental, and recreational advantages.

SUDS have been implemented on various places in the world and can include a wide range of different measures. Concepts of on-site stormwater management have growing acceptance in Australia [71], Germany [72], the Netherlands [73], and the UK [74] though still not widely and commonly applied in all settings.

A range of studies show the positive impact that a new stormwater management approach can have on cities. One such example can be found in Malmö in Sweden [75], where a combined green roof and pond system is retrofitted into the Augustenborg neighborhood. Green roofs are one measure out of a wide range of possibilities for stormwater management. For instance, Bengtson [76] established that extensive green sedum roofs with a 3 cm thick substrate layer are expected to retain 10 mm of rain before discharging water. Models run in parts of the Augustenborg neighborhood indicated that a 31% extensive green roof cover in a certain area can reduce the peak flow by 64% for a rain event statistically happening twice a year, and 27% for a rain event reoccurring once in 5 years. In addition, the runoff volume is reduced by 52% and 18%, respectively, for the same return periods [77].

The implementation of SUDS is expected to improve the quality of life in the cities and has furthermore a range of technical as well as ecological advantages. It leads to an improved performance of the wastewater treatment plants, as the wastewater is less diluted, to a reduction of energy demand for wastewater treatment and furthermore to a decrease of combined sewer overflows. Stormwater can be harvested for supply purposes, such as laundry and toilet flushing, and thus reduce the strain on other freshwater sources.

Moreover, infiltration of stormwater can contribute to recharge and maintain groundwater sources in urban areas. Infiltration of stormwater in soil layers that are hydraulically linked to local streams can support the stream's base flow. A lower peak flow reduces the risk of flooding, erosion, and uncontrolled pollution of receiving water bodies. In cities, the groundwater level is commonly lowered as a result of extraction of groundwater for supply purposes, drainage of natural wetlands, and little stormwater infiltration due to few permeable surfaces. A general decrease in the groundwater in an area can result in a lower water table in surrounding wetlands and negatively affect the flora and fauna. It should be noted that climate change is predicted to increase the overall amount of precipitation, which would in general increase groundwater levels in Northern European countries such as Denmark.

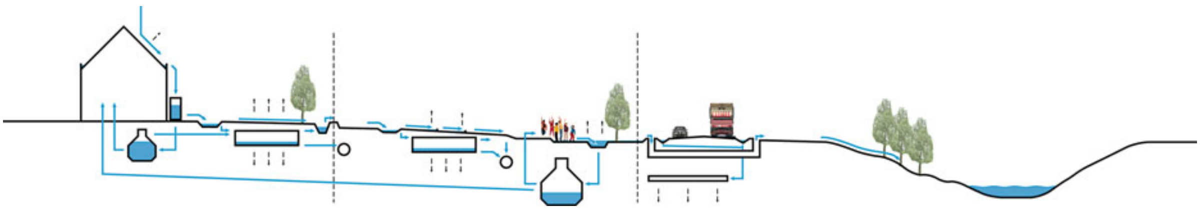
Finally, SUDS support the use of rainwater as an asset benefiting city life. People are attracted to water whether it is children playing in a puddle or adults who are happy to pay more for a house with a view to waterfronts than other places. Water increases the attraction of the environment and can contribute to a greener and richer plant and animal life.

Apart from the advantages, the implementation of SUDS bears also some risks, such as groundwater pollution from polluted soils or infiltration of runoff from heavily trafficked areas, or the unwanted flooding of low-lying areas or basements. These risks need to be known by planners and engineers and proper avoidance strategies and monitoring needs to be implemented together with the SUDS.

SUDS are a relatively new concept and not as many experiences exist as goes for conventional sewers. Some of the major aspects that emphasize the difference between conventional systems and on-site stormwater management systems are, for example, the dimensioning, the work across scales, the context dependence and the need for new collaborations, and a new way of thinking.

Regarding urban drainage systems, a good solution must cover and respond to different conditions. It must be suitable for the everyday functionality of the city and appropriately manage the risk of flooding, for example, by redirecting water to areas where the damages and negative impacts are smallest.

Furthermore, stormwater management planning is closely linked to environmental management for entire watersheds. Up to now, most projects have been implemented only at site level with little connection to the surrounding landscape [78]. Little knowledge



Green Infrastructure and Climate Change. Figure 9
Sketch of an interconnected system of SUDS elements (illustration: O. Fryd)

has been developed regarding large-scale landscape-based stormwater management systems and their potential positive and negative impacts on other aspects of urban land use and possible integration with other urban development goals. An interdisciplinary case study with the goal to develop a suitable strategy for large-scale SUDS retrofit in the eastern parts of Copenhagen (Denmark) [79] suggested that there is a need to place small-scale projects for on-site stormwater management within the context of larger-scale planning for entire watershelds. As an aim, a system of point measurements should be connected by linear elements and zones, and by this create a new green and blue water infrastructure network. Such a system design of connected disconnections would support the capacity of the single sites across special and temporal scales. Single site measures would treat the stormwater independently on a daily basis, while in case of an extreme storm event, streets and green corridors function as emergency overflow systems. Figure 9 is developed as part of the study in Copenhagen and illustrates an interconnected system of SUDS elements covering site-level, district-level, and city-level measures. It points toward the potential of urban green infrastructure to support the planning and design of large-scale landscape-based stormwater management systems, as integrated sites for retention, infiltration and evapotranspiration, and/or conveyance of excess runoff that can be linked to the planning of gardens, parks, and green corridors.

Such a citywide water system requires close collaboration between the different stakeholders. Green space management and sewer management must merge to ensure successful SUDS implementation, and as water does not know administrative borders, a planning system that brings all stakeholders to the table is required.

Flood Management

Sea level rise will challenge many coastal urban areas. In addition, increased runoff will raise river water levels and increase flood risks. More impervious urban areas and more intensive rain events will exacerbate the situation. The conventional way is to manage rivers by means of channelization, raising the dikes and installing dams. A landscape-based approach to coastal and river flood management is an emerging concept currently being explored in countries like China [80], Germany [81], India [82], the Netherlands [83], Singapore [84], and the USA [85].

In quite many cities, projects of river restoration have been implemented in the last decades, for example, revitalization of the Los Angeles River (USA) [86], Cheonggyecheon Linear Park, Seoul (South Korea) [87], Akerselva, Oslo (Norway) [88], the Aarhus River (Denmark) [89], and the river Isar in Munich (Germany) [90]. Climate change may not yet have been a strong political driver of these projects, but the outcomes are certainly highly relevant for adaptation of cities to climate change via the green infrastructure. As an example, the restoration of the river Isar within the built area of Munich will be briefly presented here. Munich is a city of some 1.3 million inhabitants located on the banks of the river Isar. The river originates in the Alps, and the city's history has been closely connected to the river as a source of water, energy, and a transport route, and the Isar is just as iconic to the city as the Alps nearby or the Oktoberfest. While the medieval city kept a respectful distance to the wild river, the Isar was channelized from the nineteenth century onward for flood prevention and energy use. The floodplains were partly built over. Still, the river is the backbone of the city's green structure with famous parks in the former floodplain.

Green Infrastructure and Climate Change. Figure 10
River Isar in Munich during a flood after restoration (photo: S. Pauleit)

In the 1990s, a major flood almost caused a catastrophe with river boards being filled to the brink. This, together with new regulations whereby safety thresholds for flooding were increased, caused a radical rethinking of the approach to flood management. It was realized that flood problems could not be solved alone by further increasing the height of the river dams. Moreover, this would have caused major negative impacts on green spaces along the river which are highly valued for recreation and therefore, it would have been difficult to get political and public support for a hard engineering solution. Instead, a strategy was adopted whereby the river bed was broadened where this was still possible to provide more space for the water. The riverbanks were remodeled to enhance access to the river for recreational purposes (water quality has been improved due to new sewage treatment systems of municipalities upstream) and to promote habitats for wildlife (Fig. 10). The river Isar restoration can therefore be considered as an example where a politically contentious situation was turned into a win-win solution by adopting a multifunctional strategy. It should be noted that this was possible due a number of preconditions that had paved the way. Among these was a long history of steadily aggravating problems with the river ecosystem that necessitated taking measures along the entire river, the outstanding role of the river for city image, a society campaigning for the protection of the river that existed for more than 100 years, possibility to renegotiate the use of the river water for power generation due to expiry of contracts, and construction of sewage plants in municipalities upstream, which improved water to bathing quality. Opening of this window of opportunities was essential for realization of the project.

The examples of river Isar and others show that landscape-based flood management systems along coasts and rivers can be fully or partly developed as part of the urban green infrastructure. Landscape-based flood management systems reflect some of the same principles as SUDS by using hydrology as generator of sustainable urban form by specifically addressing flood risks, seasonal flow patterns, and tidal water dynamics as defining factors for integrated design. Much focus seems to be on the edges between cities and their water bodies, that is, a transition from hard edges to softer and more dynamic edges. This is characterized by a change from channelization and embankment to a focus (at least partly) on temporarily wet and dry transition zones. From an ecological perspective, such zones are expected to perform well as marshes, wetlands, mangroves, and riverbanks provide some of the most diverse natural ecosystems. However, they must be designed to also comply with urban needs such as public health and accessibility. Therefore, a multifunctional strategy is prerequisite to successfully developing the green infrastructure.

The Potential of Green Infrastructure to Mitigate Climate Change

Climate change mitigation relates to the reduction of greenhouse gas emissions. For this purpose cities have a series of potentials, for example, by reducing energy consumption rates, exchanging non-renewable by renewable energy sources, and densifying cities so the need for transportation is reduced. As an example, Melbourne, Australia, aims to be CO_2 neutral by 2020 [91]. Many other cities throughout the world are currently launching initiatives to reduce CO_2 emissions and to promote a more climate-friendly development.

To some extent, green infrastructure can mitigate greenhouse gas emissions, either by directly capturing and storing CO_2 or by reducing energy consumption of nearby buildings. It should be stressed, however, that the literature is sparse and that the mitigation potential of urban green infrastructure is not well documented. The chapter heavily, but not solely draws on Nowak [42], where the potential of urban trees to modify the urban environment has been reviewed.

CO_2 Sequestration and Storage

Trees and other types of vegetation take up CO_2 when they grow. A large, old tree can store about 3 t of carbon in the stem, branches, and roots [42]. This corresponds roughly to the amount of CO_2 emitted from driving 18,000 km in a medium-sized car (based on the assumption that a car emits on average 164 gCO_2/km) [92]. As such, the uptake in urban trees is very modest compared to the total CO_2 emission deriving from a city. For Chicago, it was estimated that the yearly sequestration of CO_2 in all the urban trees totaled approximately 140,000 t, corresponding to the CO_2 emissions of all car-based traffic from 1 week [42]. Further, the improvement is only permanent if the trees, when cut or dead, are replaced by new plantings and the dead biomass is used to replace fossil fuel. Simple decay will release the entire amount of stored CO_2 back into the atmosphere. In the balance of biomass CO_2 sequestration, the emissions of CO_2 from decay processes should also be subtracted.

Increasing the amount of green in a city will only marginally meet the mitigation challenge. The main task is still to reduce greenhouse gas emissions. Still, it can be reasonable to include urban trees in a climate plan and as part of the citywide CO_2 strategy as it might serve as part of a city-branding strategy. New York City has launched the "Million Trees Programme" to increase the amount of trees in the city by 20% as a means of carbon sequestration. At present, the urban trees in New York take up 42,000 t of carbon every year and stores a total of 1.35 million t of carbon [93].

Large tree size, longevity, and high growth rates are factors that have a positive influence on trees capacity to sequester and store carbon. However, trees can only fulfill these functions when they are healthy and growing. In particular, street trees suffer from many stresses, and the average age of such trees has been estimated to be as short as 10–15 years in some cases [94, 95]. Moreover, recently planted trees often die due to bad site conditions and lack of or improper care [96]. Exact figures are rare but for instance, for Liverpool (UK) it was estimated that 39% of all newly planted street trees died within 5 years after establishment [97]. Yet, as a modeling study highlighted, street trees need to grow for at least 5–10 years before trees start to have a positive carbon balance because of the amount of carbon spent on their raising and management [98].

Urban trees are not the only way of greening the city. Lawns, shrubs, green roofs, and grass swales comprise some of the other options. Still, CO_2 storage capacity varies a lot and is mostly dependent on biomass stored in trees. A study of four residential neighborhoods in Liverpool showed a variation in carbon storage from less than 1 t per hectare to 17 t per hectare, with corresponding annual carbon sequestration rates from close to zero to 130 $kgCO_2$/ha [40].

CO_2 sequestration and storage in vegetation has a potential as an "image" of sustainability, but the impact of mitigating climate change is very modest in actual figures. To obtain larger reductions in CO_2 emission rates, urban greening can be used as a strategic tool to reduce energy demands, as presented below.

Reduction of Energy Demand for House Heating and Cooling

Hot weather in the summer period in presently temperate areas will increase the demand for air-conditioning in office buildings as well as in private houses. Yet, air-conditioning is energy demanding and expensive. Green infrastructure can potentially serve as a passive system, which can reduce energy demands for house heating and cooling.

Shading walls in summer time reduces the thermal load on buildings and hence the need for air-conditioning in warm climates. Trees should be best planted on the side where the afternoon sun hits the buildings (the southwestern side on the northern hemisphere). Deciduous trees are better than evergreen trees as the latter block the sun in winter when it warms up the building. Placing evergreen trees at the side of prevailing cold winds during wintertime can also shelter buildings and thus reduce energy loss [42]. These are significant factors in particular when insulation of buildings is not at high standards. For the homes in the US it was estimated that energy use in house can be 20–25% lower with an optimum planting of trees around them [99]. Yet, when badly placed, trees may even increase domestic energy consumption.

Other model calculations from the USA showed that 10% more tree cover can reduce energy consumption rates for cooling by 24% in Sacramento and 12% in Phoenix [100]. Most of the cooling energy savings were attributed to the effect of evapotranspiration and only 10% to the direct effect of shading and wind shielding. In the more northern city of Chicago, which has an 8 month heating season, an increase in the tree cover by 11% in an urban block would potentially reduce annual energy demands for house heating and cooling by up to 3.8% [101]. Here, the wind shielding effect was most important to reduce energy needs.

A field experiment in Sacramento where 16 trees were planted to the southeast and southwest of two houses and where indoor and outdoor temperatures, roof and wall surface temperatures, wind speed, and air-conditioning electricity use was measured during June–October resulted in an estimated cooling energy savings of 29% during the season for the two houses. Peak demand savings for the same houses were estimated to be 47% and 26%, respectively [102].

Roof and wall greening have the potential to decrease energy consumption of buildings for cooling buildings by improving insulation and reducing thermal loadings. In hot climates, reduced heat load during summertime is of significant importance. As an example, cooling load for a two-story nursery school building in Athens (Greece) was reduced by 6–49% during the summer for the whole building and by 12–87% for the top floor [103]. A study of an eight-story building in Madrid in Spain identified that a green roof reduced the building energy demand by 1% annually and 6% during the summer [104]. In a peak hot weather situation, the cooling load was reduced by 25% for the floor below the green roof. This indicates that green roofs have the greatest effect on energy consumption for buildings with a large roof area compared to the height of the wall, such as single-family houses, warehouses, and big box stores.

This way of reducing energy by tree planting, roof and wall greening has the spin-off of greening the city. However, potential conflicts with modern "green architecture" [105, 106] may also arise as, for instance, trees, wall and roof greening may be an obstacle for collecting solar energy by photovoltaics. This is certainly an important area for cooperation between architects and landscape architects to solve emerging conflicts and create synergies in the integrated design of the green infrastructure and green architecture.

Finally, vegetation, and in particular trees and shrubs have also the capacity to capture air pollutants [42]. More green may offset to some degree the potential increase of air pollution caused by intensification of the heat island. However, as with carbon sequestration, few data indicate that this effect will be quite limited [42]. Therefore, planting more trees and shrubs is not to be considered as an effective means solve the problem of emission of carbon dioxide and air pollutants.

Vulnerability of the Green Infrastructure to Climate Change Impacts

Green infrastructure has a series of potentials in terms of climate change mitigation and adaptation in urban areas. At the same time, green infrastructure is vulnerable to the impacts of climate change. Plantings, habitats, and species are challenged by higher temperatures and changing precipitation patterns, and the thermal benefits of evapotranspiration rely on lush vegetation. Furthermore, as Wilby and Perry [107] state in a review, there may be increased competition from exotic species, disease and pests may spread, and sea level rise can threaten rare coastal habitats: "Earlier springs, longer frost-free seasons, and reduced snowfall could further affect the dates of egg-laying, as well as the emergence, first flowering and health of leafing or flowering plants. Small birds and naturalized species could thrive in the warmer winters associated with the combined effect of regional climate change and enhanced urban heat island."

However, the database is very limited at the moment to establish, with any certainty, the impacts of climate change on the urban green infrastructure and to its ecosystem services. In the following, information from the ASCCUE project will be presented to discuss potential consequences of climate change on the capacity of green space to mitigate the heat-island effect.

Based on the climate scenarios used in the ASCCUE project, it was estimated that periods without water content available to plants in the upper 30 cm of the soil layer would increase from currently less than 1 month during summertime to up to 4–5 month in the inner city of Manchester (UK) in the high-emissions scenario. As a consequence, grassland would dry out and loose its capacity to evapotranspire water. Certainly, reliability of these estimates is low, in particular, as regional soil maps had to be used due to lack of better information on urban soils, which are known to be highly variable [108]. Nevertheless, the figures indicate the potential challenges that may arise for management of the green infrastructure under a changed climate.

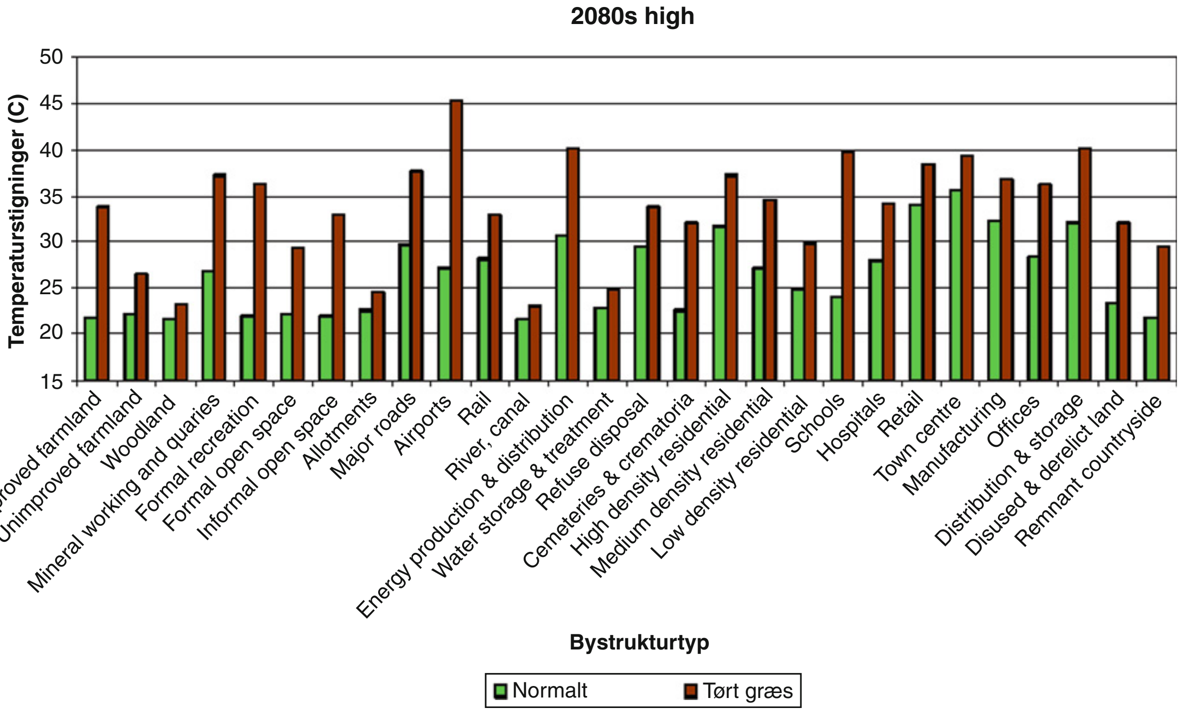
Temperature differences with and without the provision of evapotranspiring grassland for 29 urban morphology types in Manchester are shown in Fig. 11. On a hot summer day, surface temperatures would be up to 70% higher on dried-out vegetation than on lush vegetation. In particular, areas with large expanses of lawn such as public parks, playing fields, and also schools would suffer. This points to the increasing need for proper water management to ensure well-growing vegetation or the choice of drought-tolerant vegetation. As concerns the former, mechanisms of water storage for irrigation during times when there is abundant rainfall need to be conceived. Reducing the amount of lawns in favor of trees and shrubs, which can access the water in deeper layers of soil with their roots, should also be considered where possible. However, trees require sufficient space for their roots.

Taking street trees as an example, water stress already occurs as a result of limited soil volume and small rooting space in planting pits combined with soil compaction and generally limited stormwater infiltration in built-up urban areas [109, 110]. Longer dry periods and rising temperatures will increase water stress and result in street trees dying if no proper management regime is installed. For instance, studies from Copenhagen (Denmark) indicated that larger planting pits in combination with improved soil substrates and irrigation can significantly improve growth conditions for street trees [109]. However, taking water for irrigation from the water supply system will become increasingly problematic under climate change. Another option is to combine irrigation needs with stormwater management, for example by discharging stormwater runoff from pavements to street trees. Such systems are, for example currently tested in the City of Stockholm, Sweden [111].

With changing precipitation patterns, higher temperatures, and later spring frost, the appropriate selection of species is an equally important approach to reduce the vulnerability of green infrastructure to the impacts of climate change. To address the challenge and to raise a discussion on the issue a Climate-Species-Matrix was developed for urban trees in Central Europe [110]. The study identified current regions analogous to the expected future climate in cities in Central Europe (i.e., less than 500 mm precipitation per year and average minimum temperatures between −17.8°C and −23.3°C). It resulted in a list of species with an increased focus on species originating from continental Central Asia and the continental northeastern parts of North America. Here, native species have evolved under conditions that may be similar to those experienced in urban areas in North and Central Europe in the future.

Future Directions

Climate change will imply significant consequences for the urban climate and the urban hydrology. The urban heat-island effect will increase if no action is taken. But by increasing the provision of urban green space, the



Green Infrastructure and Climate Change. Figure 11
Surface temperatures on a hot summer day in a 2080s high scenario with lush vegetation and dried-out vegetation ([120] with permission from author)

temperature rise resulting from global warming can be mitigated. More intensive rain storms resulting from climate change will challenge the capacity of existing urban drainage systems and increase the risk of flooding. Implementing additional landscape-based stormwater detention, infiltration, evapotranspiration, and conveyance measures can compensate for changing precipitation patterns. By promoting urban green infrastructure, a network of green spaces can be implemented in the city to mitigate climate change and to adapt cities to the impact of climate change. A green infrastructure, which is multi-scale, multifunctional, interconnected, and reflecting hydrology, is a major generator of sustainable urban form. Yet, the green infrastructure needs to be robust to cope with climate change. This has implications for the design of green spaces, including preparation of planting sites and species selection.

Landscape design to face climate change is an emerging concept, which can assist in sustaining cities in an increasingly urbanizing global context. It calls for continuous loops of collaboration, knowledge exchange, experiments, and learning by doing.

A recent symposium with 40 leading European experts [112] led to the development of a framework for research on urban green space. A total of 35 research questions were specified regarding the physicality, experience, valuation, management, and governance of urban green space. At least five of the research questions were directly related to the future role and capacity of urban green infrastructure in the light of climate change. These were primarily related to the physicality of urban green space and included the desired documentation of the "*direct and indirect effects of the climate changes on urban green spaces and how these changes impact people's well-being in urban areas*," "*how resilient current green space designs are to climate change and how resilience can be improved*," and "*how the resilience and adaptability of urban areas can be enhanced to future economic, housing and environmental demands through appropriate design and management of urban green spaces*." Additionally, 15 research questions were related to aspects of ecological functions, the public goods, and market benefits of urban green infrastructure, interdisciplinarity, and the management and governance of green areas, all addressing appropriate next steps in the exploration, analysis, and understanding of the potential of urban green infrastructure as a tool to face the global challenges of climate change and urbanization.

Adoption of a multidisciplinary approach to the development of the multifunctional green infrastructure is needed, including not only landscape architects and urban planners but also traffic engineers, hydrologists, biologists, sociologists, and economists. Importantly, urban green infrastructure calls for a participatory, socially inclusive approach to its planning and implementation as it will go across public and private land and affect all citizens in different ways. This challenges the sector-based distribution of work and responsibility areas currently prevalent in most public administrations. Multi-scale approach also involves interinstitutional collaboration and close cooperation between local, regional, and national authorities. Research in the field is emerging in Australia [113], the Netherlands [114], and the USA [115]. The examples from Copenhagen and Munich in this paper have shown that there is increasing potential for such an approach as disciplines realize the limitations of sectoral approaches.

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Green Roof Infrastructures in Urban Areas

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Article Outline

Glossary

FLL The Landscape Research and Development Society (FLL) nonprofit organization was founded in 1975. Its mission is to research, produce, and disseminate all the various landscape development principles, guidelines, and specifications for the assurance of environmental quality [1].

FBB The Green Infrastructure Association (FBB) is a specialized group that was founded by some members of FLL to focus more specifically on green building. The FBB is the German counterpart to the American industry association Green roofs for Healthy Cities (GRHC) and one of the founding members of the World Green Infrastructure Network (WGIN). The German Word "Bauwerksbegrünung" has no translation in English – Green infrastructure in the sense of FBB is focused on all forms of urban green.

Extensive green roofs (EGR) Also called natural green roofs, eco-roofs, and oikosteges in Greece are vegetated roof constructions that require low to no maintenance. Drought-adapted plant species are used to create a self-sustaining vegetated surface suitable for nearly all types of buildings. Growing media is usually less than 10 cm, or 3 in. deep [2]. The term "Natural Green Roof" or oikostegi, coined by the authors, denotes a green roof where the main interest is in maximizing natural endemic biodiversity on vegetated roofs. These systems can incorporate irrigated areas with rain or gray water. Natural green roofs are designed, engineered green roof systems which enlist the help of the natural environment. Natural green roofs may also be engineered in such a way to include intensive green roofs on occasion.

Intensive green roofs (IGR) Also known as roof gardens are garden structures on top of buildings and other artificial urban surfaces. In most cases, the growing media is more than 20 cm deep; for trees it can be more than 1 m. IGRs, with structures including lawns, planter boxes, shrubs, and small trees, require the same maintenance as traditional gardens; therefore, some question their environmental value.

Stormwater runoff Rainwater running off impervious surfaces.

Green infrastructure Overall phrase in North America for all types of green roof technology and other types of greenery on buildings, like vertical greening, living walls, and indoor greening systems. Green infrastructure in a wider sense includes photovoltaic technology and rainwater management.

Growing media Engineered substrate for green roof purposes. Green roof substrates typically have low nutrient content and high drainage rates. Typical materials are expanded slate, shale, pumice, or recycled construction material such as broken ceramic tiles.

Green infrastructure Broad term in the North America for all types of green roof technology and other types of greenery on buildings, like vertical greening, living walls, and indoor greening systems. Green infrastructure in a wider sense includes photovoltaic technology and rainwater management. This term also describes the range of materials and technologies used to enhance urban environments. In addition to green roofs, this term also encompasses other related systems such as vegetated facades with climbers or living wall systems, indoor greening systems, rain gardens, photovoltaic systems, and other technologies. Roof greening can be combined with living walls, indoor plants, and ecological landscaping to enhance the built environment. The USEPA refers to structures specifically intended to manage wet weather as green infrastructure.

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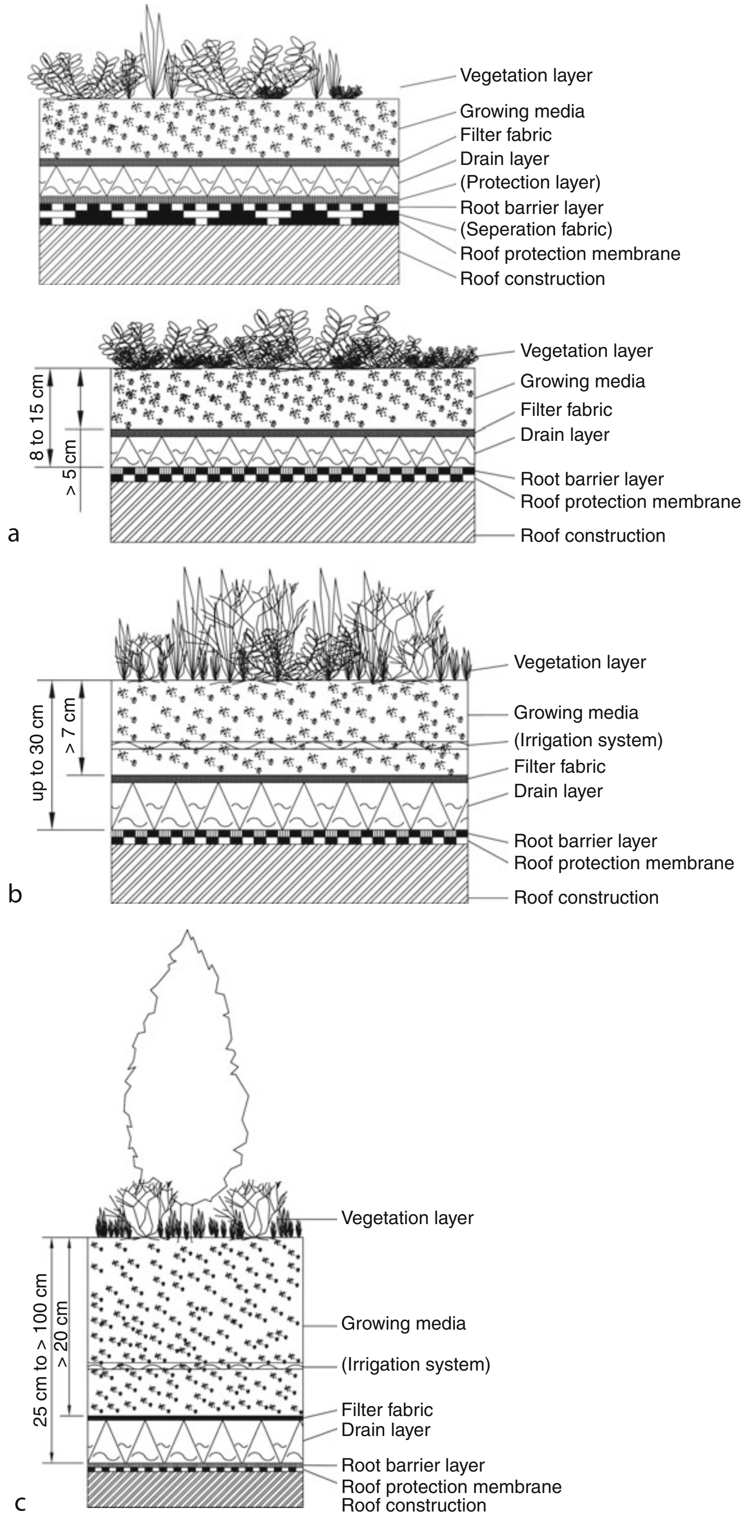
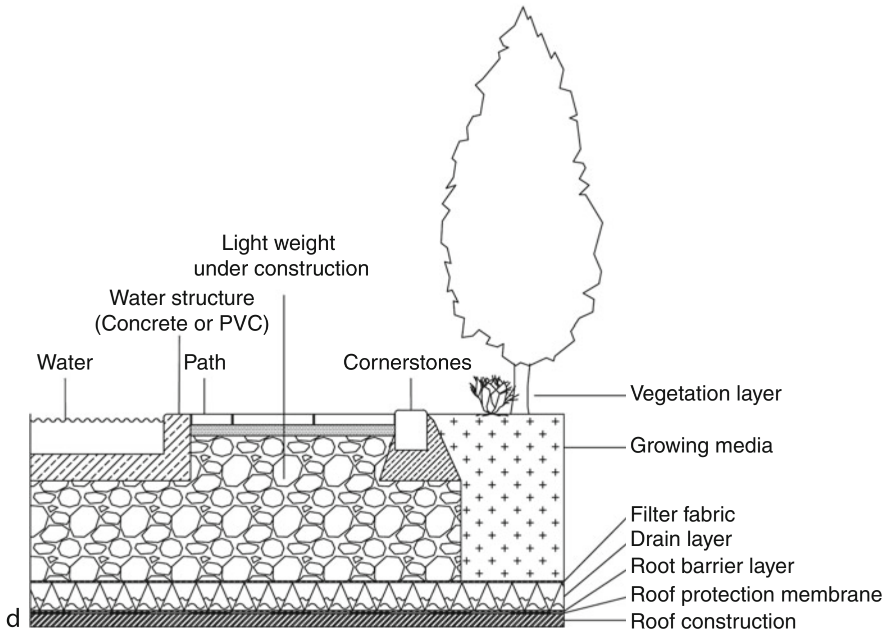


Green Roof Infrastructures in Urban Areas. Figure 1 (Continued)



Green Roof Infrastructures in Urban Areas. Figure 1
The first schematic cross section illustrates the principles of green roof structures. (**a**) Details the one-layer solution without drainage components. This could be difficult in a damp, wet climate. (**a1**) is a multiple layer solution, typical construction from various suppliers. (**b**) Semi-extensive means, irrigation is included. (**c**) Intensive roof garden. (**d**) Plaza deck construction on garages and similar structures with high load capacity

Leadership in Energy and Environmental Design (LEED) This is a US-based rating system by the US Green Building Council (USGBC). Benchmarks focus on energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship. The categories of achievement are silver, gold, or platinum. In Australia, a similar rating system uses "stars." After an extensive debate about the merits of such certification systems, Germany set one up in 2009. Certification can be an effective type of marketing; however one critique of existing systems is that there is not enough weight placed on vegetation.

Low-impact development (LID) A storm water management and site-design technique to mimic the situation before construction. Water usage, evaporation, cooling, and water storage and drainage are such benefits of green roof infrastructures.

Definition of the Subject and Its Importance

Definition

Green roofs are engineered constructions that include environments suitable for well-adapted plant species. In most cases, these types of roofing have a longer life span than conventional roofing surfaces. The following elements are built on top of the roof structure (from the bottom to the top, see Fig. 1):

– The underlying protective layer is made of an impervious material such as bitumen, rubber, polystyrene, or other similarly adequate technical materials, in short, roof protection membranes.
– Additional, root barrier layers are available to prevent the root penetration of lower layers. These are known as separation fabrics or geotextiles.
– This is commonly followed by a separate water-retaining layer, which could be a natural porous

stone material or an artificial retention mat; in short, this is a drainage layer.
- On top of this layer, a filter fabric separates the retention layer from the next layer: the growing media.
- The growing media is, in most cases, a specially mixed lightweight soil material with carefully selected ingredients for storing rainwater. Growing media are mixed for different purposes (for example, extensive green roof growing media differs from roof garden media in nutrient and humus content). Intensive roof garden growing media differs in that in the upper levels there is a higher content of humus and on the lower levels lower humus content.
- The vegetation layer can range from a shallow layer with mosses and only a few taller plants all the way up to full-blown roof gardens. As such, green roof maintenance requirements can be as little as an annual inspection or as much as is usual for ordinary gardens. The success of the vegetation layer depends on the careful selection of the other green roof layers. For example, if the goal is to plant trees on roof tops, a special combination of all these components is necessary (After [3]).

The maximum weight of the construction must be calculated carefully. On average, it varies between 40 kg/m^2 (this is about 8.33 lb/ft^2) and can rise upward to about 350 kg/m^2 (71.7 lb/ft^2, for conversion factors, see [4] on roof gardens, including the weight associated with water storage. Extensive green roofs should be able to store a minimum of at least 20 L/m^2 of water. Compared to this load, the weight of all the plant components is relatively small.

The longevity of green roofs depends on whether they can be easily accessed with the basic equipment needed for the success of the project as well as repairs. Maintenance and repairs must be planned carefully. Certain areas of the roof like, edges and places around roof fixtures like skylights or climate control systems can be prone to structural damage. Architects often want to install green roofs on very steep roof inclinations and on very tall buildings. These technical and biological limits challenge green roof professionals. It is the duty of green roof specialists to assess the limits which are set. Uncontrollable aspects of local climate, like wind, temperature, and the intensity of storm events and solar exposure can set limits to what is feasible from an architectural design perspective and ideas about developing living surfaces on roofs and facades.

In Germany [1], two main types of vegetated green roofs are observed:

- Extensive green roofs are large lightweight constructions. Most consist of a layer of under 10 cm deep covered by drought tolerant plant species including mosses, sedum sp, other succulents, wild flowers, aromatic herbs, and a plethora of pioneer species. Commonly, no irrigation is installed, particularly in temperate climate experienced in Central and Northern Europe and North America and only one annual maintenance visit occurs. These structures are possible on nearly all types of flat buildings covered with gravel protection layers; gravel has nearly the same weight as green roof materials but gravel has relatively no environmental value.
- Intensive green roofs, synonymous with roof gardens, are fully maintained with garden structures similar to those on the ground level. The first step in planning such constructions is a careful calculation of the loading capacity.

Recently, [1] a third type, called "simple intensive green" has been developed. These are green roof constructions with a little irrigation on demand, a wider range of plant species, and a little maintenance. Shrubs and garden plant species are suitable for such green roofs. Another difference is the need for maintenance. Extensive green roofs usually only need one inspection a year. The simple intensive green roofs or roof gardens do need maintenance, and are thus more similar to ground-level gardens.

The phrase "grass or sod roofs" is used to describe extensive green roofs in the Northern European region, while "Living roofs" is the most commonly used term for green roofs in the UK. They distinguish between "green roofs" and "biodiverse green roofs," which are characterized by a wider range of growing media types at various depths. This creates a wider range of microhabitats. Furthermore, green roof researchers in the UK also talk about "brown roofs" or roofs with shallow layers of growing media and a sparse vegetation cover, mostly developed for insects and nesting birds. The presence of birds like the Black Redstart on green roofs is a key indicator of success about which people in the UK have become especially emotional. Observations like these help to promote green roofs. In Greece, there is growing interest in another form of extreme natural green roof called an Oikostegi (from the Greek "οικος" meaning home, abode, living quarters, and "στέγη" meaning roof, shelter, protection, den). Oikosteges/οικοστέγες/ are designed for the most extreme built environments on Earth, namely, earthquake zones, which permit only ultra-lightweight building greening systems. In addition, oikosteges are designed to be low to zero maintenance and low to no irrigation in extremely hot, dry, windswept, so-called urban canyons like Athens. This is green infrastructure at its hardest core and at its most extreme.

Installations at prestigious locations such as the Greek Treasury, in Constitution Square, opposite The Greek Parliament in Athens have been acclaimed with rave review by specialists, academia, and the media. Countless species of butterfly, spider, and other insects like honey bees and ladybirds attract numerous species of song birds, which have begun to nest in the center of this sprawling metropolis. This ecosystem has been named the "Meadow of Constitution Square" a touching acknowledgment that nature has begun to establish a foothold in the once barren, windswept capital which was the birthplace of democracy, the rule of law, politics, philosophy, Western medicine, logic, science, the Olympic games to name just a few of the contributions that Greece has made to humanity.

It should be also noted here that Greece has the richest biodiversity in Europe boasting fully one third of all indigenous species on the European continent. The growth of cities like Athens had all but banished this abundant natural wealth from its home. Oikosteges represent a hopeful sign that Athens and Greece as a whole with its rich natural environment is now reestablishing itself to take the place it deserves as an inspiration and testament to the world of what is possible.

Green roofs are also characterized by their technical structure. The non-ventilated flat or "warm roof" is constructed with the insulation under the waterproofing layer. In contrast, on "inverted roofs" the insulation layer is installed on top of the waterproofing layer. These inverted roofs have received a lot of attention because this layering can protect the waterproofing and also be used to prevent leaks. However, there are also some disadvantages, like, for example, reduced insulation function if the thermal insulation is exposed to water. An open debate about such details of building physics must take place between the roofer and the landscaper executing the green roof. Surface sealing, either with an artificial layer or with liquid sealing components must be selected carefully. There are regional differences in such construction materials. All layers must be qualified as "root resistant" and be secure against aggressive roots. Such layers contain, in many cases, components to prevent root penetration [2]. It should be obvious that these layers should not include poisonous substances. These components could be washed out into the sewer systems or could be a problem for the roof vegetation.

Green roof technology has become internationally renowned in the past few years. The books recommended at the end of this chapter offer a wide range of basic information from various regions in the world.

Introduction

Introduction – Worldwide Historic Roots of Green Roofs

Like many other ground-breaking ideas, the basics of green roofs are simple and some historical examples date back more than 2,000 years [3]. A water barrier layer and an additional layer of growing media make it possible to cover a building with plant material. This coverage protects the building and stabilizes temperature fluctuations. That is why green roofs can be found worldwide from the hot and dry climates of the African desert zones where there are examples in places like Uganda, to the Northern European zones with long cold frost periods, such as the Iceland sod homes. These prototypes are the predecessors of extensive green roofs.

Roof gardens or intensive Green roofs may have originated from the "hanging gardens" of Semiramis (Babylon). Intensive green roofs can only be built on flat roofs and are quite similar in structure and form to a ground-level garden. In some Mediterranean countries, flat roofs were traditionally used as recreational space for spending time at home in the evening breeze.

Roofs do not necessarily have to be flat in order to be greened; it is also possible to have green sloped or pitched roofs. The grass-covered tombs in the ancient City of Pamukkale (Turkey) are examples of this. Water tanks with a grass roof structure are common in some countries in Southern Europe. On North European pitched rural farmhouse, green roofs are found in many regions. Roof gardens became especially widely distributed [4], creating green islands in urban environments in the 1920s with a peak of interest in the 1970s. Roof gardens as recreational areas on shopping malls and hotels have also become fashionable.

The first emergence of modern green roofs was observed in the 1860s. During this period of industrialization, roofers developed methods of covering their housing tenements with a gravel layer and turf to avoid the risk of fire. Between 1860 and 1920, similar ideas grew in many German Cities. These older green roofs were a cheap way to protect the sensitive layer of tarred cardboard used for roofing at the time [5]. Vegetable gardens were also planted in these first roofs. All these green roofs were erected above a wooden support construction [6].

In the 1920s, several roof garden projects were documented in the literature of the historic garden library; (see the online Databank of the Technical University of Berlin, (http://freitext.ub.tu-berlin.de/gartenkunst.html) using the German word "Dachgarten" as a search word. At the time of writing (April 2010), 130 titles are available dating from the beginning of twentieth century concerning green roofs.

Since the beginning of the twentieth century architects, like Le Corbusier and Oscar Niemeyer have included roof gardens in their designs. Some of these early modern roof gardens still exist today. One of the most famous is the roof garden on the Rockefeller Center. Other examples like the roof gardens at "The Bund" in Shanghai were also built at that time. In the late 1930s, LeCobusier, Oscar Niemeyer, Lucio Costa, and Roberto Burle Marx created roof gardens as part of a workshop at the Ministry of labor and work in Rio de Janeiro, which can still be seen today. The landscape Architect Burle Marx completed nearly 100 roof garden projects mostly in South and North America, but also in some other countries of the world.

Flat and green roofs were the preferred style in "Bauhaus" architecture. Planners in the 1920s were fascinated by the open amenity spaces on the roof tops of modern Cities. In 1929, the storehouse Karstadt at Berlin-Hermannplatz was one such famous building. It was well publicized, and *the* place to stay at that time [4]. In its first year, in 1929, the young Roberto Burle Marx began a 1 year stay with his family in Berlin, studying vegetation in the Botanical Garden and Art. Burle Marx is regarded as being as the landscape Architect of the Bauhaus team, newer publications describe him as this [7, 8]. He is considered to be one of the most innovative landscape architects in the twentieth Century and a pioneer of roof garden technology since the 1940s all over the world. Modern examples are documented as award-winning projects in the USA [9, 10].

Maintenance of these early roof gardens was similar to that of gardens. They were high-quality recreational spaces where the affluent could spend their leisure time. No publications discussing maintenance or issues of ecology are mentioned from this era.

It can be deduced from the painting by Carl Spitzweg, called "The poor poet" 1837, that living in a roof apartment entailed long periods of poor living conditions. In the winter time, it was too cold and in summer it was too hot. This is still the case in countries like Greece. Additional insulation provided by rooftop greenery created better living conditions in the top floor of buildings. This idea, to take advantage of additional insulation while bringing nature back into cities, gained popularity in the years following World War II.

The second emergence of green roof technology in Germany occurred in the late 1970s. A movement of urban environmentalists tried to bring nature back into Cities. A key thinker at that time was the Garden stylist LeRoy who had ideas about "natural gardens." People began to reevaluate urban areas [11]. The first ecological studies of green roofs began during this time. Among the pioneers in Germany was, for example, the Architect Minke in Kassel. His focus was the energetic performance of affordable housing. He learned from ancient African architecture and designed simple, modern solutions for "green architecture" in hot climates [12].

Famous artists at that time Friedensreich Hundertwasser and Ben Wargin promoted the concept of more natural cities and especially nature on buildings. But they were not architects. It was a challenge during the following years to materialize these concepts [13].

The Green Roof Movement in Germany

Roof gardens are a well-established technology in many countries. Hotels, holiday resorts, plaza decks, and similar institutions are covered with green roofs in various countries [4]. The main difference between the early stages of the roof garden movement and today is the current focus on ecological function, local plant species selection, and environmentally friendly construction technology.

A water storage and drainage layer can be installed underneath a roof garden, which can then be used as a recreational space for the users, citizens of the entire building. That is the position today. Lots of these older roof gardens failed over the years. Materials knowledge and maintenance techniques have grown over the years. Knowledge has been accumulated over the decades, which means that nowadays green roof technology is vastly superior to earlier attempts.

In the 1970s the so-called "National Nature conservation act" was updated in Germany. Urban areas were included as areas where wildlife should be protected. Local indigenous wildlife was targeted in this act. Naturally occurring urban plants were considered worthy of protection. A new urbanism shifted away from erecting of new neighborhoods on the outskirts of the city, and began to rethink quality of life in urban areas while searching for different places to construct more new apartments. Roofs, which had hitherto been used to dry washing, presented an ideal space to develop green roofs and then develop quality apartments in those buildings.

The Nature Conservation foundation in Berlin "Stiftung Naturschutz", an interdisciplinary cooperation of architects, planner, and ecologists started to erect such Eco – Roofscapes in Berlin. In many other Germany Cities similar activities started to enhance the quality of life in inner cities using greenery. Community projects such as backyard greening, green facades, and roof greenery were important. The use of local plant species was also a focus. Less emphasis was placed on roof gardens.

The FLL guidelines, which focus on plaza decks and green roofs, integrate both stages. The first FLL guidelines came out in 1982. They addressed all green roof varieties from the extensive to the roof garden types. The first English version was printed in 2002 and then updated in 2008 with the second edition [1].

Disseminating the Ideas of the Modern Green Roof Technology

The idea behind green roofs is basically simple; combine a waterproofing barrier, a water storage and drainage layer, a designed growing media (not typical garden soil), and the initial vegetation – that's all.

Looking in more detail, there are several concerns related to warranty that must be acknowledged. German homeowners expect their green roofs to be guaranteed for as long as in minimum warranty periods for traditional pitched tile roofs last. If the vegetation cover is not sufficient, wind and storm water erosion can present an increasing problem over the years. An annual inspection should be made to identify any problems. A good quality green roof should have plant coverage of more than 60%. This means that there will be a minimum amount of weeding necessary [14].

The German model has also been successful because of the cooperation between researchers, manufacturers, and planners, under the FLL guideline group. Green roof technology was executed according to certain norms in order to deliver secure, basic, brand-independent solutions. The FLL-approved structures can occasionally be copied, in part, in other countries with similar building codes and climates as Germany. In countries with radically different building conditions and climates, application of such guidelines is disastrous, to say the least. Many aspects of green roofing which are country or region specific due to the different building codes in different countries and other factors like climate, which affect green roof design and implementation make application of standards established in Germany rather impractical. Despite this, at the European Union level, a CEN Standard working group has started to work on an attempt at a European guideline; this will take time and is probably not practical (please see the discussion about "Green Roof Incentive Programs" below). The results of these studies may be, in part, used to help form the starting point for attempts at drafting potential national regulations. In the USA, similar activities are also underway to set up standards at the national level. The first standards have been prepared and published [15, 16].

Germany is a mature market where more than 10 million square meters of new green roofs are built each year. In neighboring countries, like France, about 0.5 million square meters are now being built each year. The movement exists in about ten European countries.

Green roof activities started to increase in North America around 2000. Since 2003, the North American Association "Green roofs for healthy Cities" hosts annual conferences to disseminate the green roof concept in North America and the world. In many Asian countries, especially Japan, Korea, and Singapore, many green roofs have been constructed in the last 10 years. In contrast to the Western world, these activities are not organized by private corporations. For example, there are incentive programs to support green roof activities in about 50 cities of Japan. In China, many green roofs are part of new city concepts. In addition, Shanghai pledged to erect about 100,000 m^2 of new green roofs in 2009. This figure was achieved in the middle of 2009. In Thailand, preliminary green roof studies have been conducted, and more are planned. The majority of the Asian projects are focused on roof gardens to offer additional city recreational space in the mega-metropolitan areas. Extensive green roofs are increasingly used to cover bus shelters and other such structures. The number of hot summer days in sprawling Asian Cities has increased in the last decade. The cooling potential of green roofs as well as reductions of the peak storm water runoff is important benefits for these regions.

In Scandinavia, especially in Norway, grass roofs are a typical construction on old farmhouses. Such structures are not very exportable to other countries for a number of reasons, but they are regionally adapted to this climate. A resurgence of construction of these types of roofs, for summer homes, has experienced a renaissance in recent years. A few cities, like Oslo, and others have been slow to set up general guidelines for green roof projects. They are focused more on architectural design competitions to promote such environmental friendly roofing technologies.

Other countries, like, Spain, Italy, and Greece have also made strides with several new green roof projects in recent years. These consist of both roof gardens and extensive green roofs. In Spain and Italy, about 500,000 m^2 of green roofs have been installed recently. In the other Mediterranean countries, like Greece, where flat roofs are typical, and the potential benefits of green roofs great, roof greening was seen as unrealistic in the past for various reasons .This changed in 2000 when a team of researchers worked for 5 years to design a Greek roof greening solution, which is adapted to the Greek building code and severe Greek climate. As noted earlier this system is called "oikosteges" and was installed on The Greek Treasury, which is located opposite the Greek Parliament, in the summer of 2008. This installation has been studied twice by the National Metsovio Technical University of Athens by Drs. Rogdakis and Koronaki. These studies concluded that oikostegi significantly effects the thermodynamics of the Treasury leading to appreciable reductions in energy requirement. Photographs of this project can be seen at http://oikosteges.gr/index.php/photogallery.

On behalf of the European Association of Green Buildings (EFB), a move was made to set up a European standard for green roof technology in Europe. Such a law would have to focus on the basics of the technology. In this proposal, each country is then requested to adapt this framework law to their specific national needs. For Germany, this would be a step backward since the current FLL guidelines were updated in 2008 [1].

Green roof projects have been registered in more than 40 countries in 2010; see www.worldgreen roof.org). The focus differs among the various climates and regions, but the benefits are quantifiable in all countries.

The main benefits of green roofs are as follows – First of all, green roof structures last longer than non-green roofs. The longer life span and decreased maintenance cost of the roof is one of the first ways that economic benefit is achieved through implementation of these structures. Different calculation programs demonstrate such benefits. For some examples, refer to Table 1. One current interactive system is the Green roof calculator [17].

Green Roof Incentive Programs

In Germany, in the 1980s, most cities set up programs to encourage urban greening. The basis for these measures was the Environmental nature protection law, updated in the late 1970s, which stated that all regions of Germany had to work on implement urban greening plans. Not only did the regions have to set up specific laws, but the cities also had to set up rules for incentives and tax breaks. An overview of all these different regulations was collected in three rounds of questionnaires distributed by the FBB; see lists on www.fbb.de.

In conclusion, it can be seen that government incentive programs resulted in the development of

Green Roof Infrastructures in Urban Areas. Table 1 Selected economic studies about the green roof benefits

Type of study	Source	Results	Comments
National survey of extensive green roof cost – benefits in Germany	[18]	Costs: Extensive green structure (m^2): €17, Maintenance 40 Years €17 additional static. €10–44 costs. Benefit: Costs – longer lifespan (up to €37) – reduce rain tax (up to €32) = profit of about: 25€/m^2	Until 2002 no calculation of energy savings had been completed Costs are based on German rates in 2002 which are close to those in 2009
Phillips Eco-Enterprise Center – case study – Warehouse after LEED criteria USA	[19]	Costs of the extensive roof $78,000 ROI, annual return – $1,000	Not calculated energy savings, study not complete
US case study for an affordable neighborhood in NYC – USA	[20]	Break even point after 15 years/return on investment	Calculation investment, energy savings etc.
National comparison Germany, Brazil, USA	[21]	Over the lifespan of 90 years, the profit of a roof garden is the highest: plus $1,200/$m^2$. Extensive roofs lost value ($180/$m^2$) as did Bitumen/gravel roof (minus about $300/$m^2$	Various differences in traditions, technology, and level of salaries
City Study Toronto: (CA)	[22]	If 50% of the roofs of the city of Toronto were extensively greened, there would be annual cost savings: $37 million	See full study on internet as pdf on the web page of city of Toronto. The results are a summary of the Toronto action plan
Portland City Study – USA	[23]	If flat roofs in a warehouse district of Portland were greened, the cost savings of the reduced storm water entering the sewage system is enough to pay for all these green roofs and reap long-term benefits	These results were integrated City of Portland action plans
Life cycle assessment of Green roof systems in Hong Kong	[24]	In tropical climate, green roofs double the life span of roof materials, reduces energy costs for air conditioning systems. Green roofs are an economically viable solution for investors	Available on web page of University of Hong Kong

backyard greenery, green facades, and green roofs in the 1980s. Later on, in 1990, one of the most successful pieces of incentive legislation was implemented whereby homeowners could receive storm water amelioration tax breaks for installing green roofs.

Storm water taxes penalize runoff created by built surfaces, such as roofs, because it burdens the public sewer system. In Germany, such a tax is about €1/m^2 of built surface. Locally, legislation varies between no rebates for roof greening right up to a 100% storm water tax exemption. On average, in Germany, across the board, this equals about €0.50/m^2 of green roof [25].

Today, in late 2009, the implementation of green roofs is well established and is included in about one third of all German building plans for permit submission. In Berlin, there is a government department that is responsible for guiding public building projects, monitoring selected key projects, and publishing basic information and guidelines for public housing and public construction sites (see: http://www.stadtentwicklung.berlin.de/bauen/oekologisches_bauen/index.shtml).

Green Roof Policy in Other European Countries In all other European countries, roof greening legislation is more recent than the laws found in Germany. In the 1980s, Austria, Switzerland, The Netherlands, and Hungary began to follow Germany's lead. The focus was different and simplified. In Austria, roof gardens were the focus of interest. In Austria, recreational space in Vienna and other large Austrian Cities was at a premium. The focus of the green roof movement in Switzerland is on the biodiversity of extensive green roofs. Similar tendencies, among other trends, can be found today in the UK and Sweden.

Regulations at the national government level are foreseen for other countries by late 2009. Some cities are forging ahead. In the UK, London has set up a green roof city policy for the coming years. Many green roof related themes can be found on the official city of Greater London web site (http://search.london.gov.uk/search, key words living roofs). In June, 2009, an internet search returned about 1,620 related links. Other British cities are behind London, but advocacy groups are forming in many British cities. In Ireland, in 2007, thanks to the Dun Laoghaire Authority, the first seminar to promote green roofs was held.

Worldwide Distribution Over the last 10 years, many other countries have begun to write green roof policies. This has led to the growth of roof greening around the world (Table 2). In the USA, about 1,000,000 m^2 of green roofs were installed in 2008. Between 2008 and 2009, an increase of 25% of square meter age was calculated by the national trade association (survey, done by Green Roofs for healthy Cities www.greenroofs.org). In Mexico City, in 2007, 10,000 m^2 and in 2008 8,000 m^2 green roofs were constructed with incentives given by the metropolitan Mexico City government and the current number of Extensive Green Roofs (EGR) constructed with the support of City administration incentives are now about 25,000 m^2. (Welcoming remarks Marcelo

Green Roof Infrastructures in Urban Areas. Table 2 Fact Block, selected numbers on green developments around world

Numbers	Locality	Description	Source
7.5%	Berlin	Calculation of the total percentage of green roofs in Berlin City. This is the number calculated counted only for the quarter Berlin – Kreuzberg	B
32%	USA	Growth of the Green roof market between 2007 and 2008	A
8,000 m^2	Mexico City	An area of public green roofs, officially opened by the lord mayor of Mexico City in 2008	C
53,000 m^2	Chicago	Chicago is the number 1 green roof builder in the USA. The total number of green roof projects presently installed are 84	A
100,000 m^2	Shanghai	Green roof area pledged for installation by 2008, the goal was achieved. Since the beginning of the campaign in 2003, 500,000 m^2 have now been installed	D
600,000 m^2	Beijing	Total area of green roofs installed in the city as of 2006	G
310,000 m^2	USA/ Canada	The total area of new green roofs installed in 2008	A
1,000,000 m^2	France	The total green roof area expected annually	E
11,000,000 m^2	Germany	This is the rough estimate of new green roofs built each year in Germany, two third of these are extensive	F

A: Green roofs for Healthy City, 2008 Green roof Industry survey
B: Koehler, own survey in 2008, (prepared for publishing at Cities Alive, 2009)
C: Personal communication, Tanya Mueller, Amenamex in July 2009
D: China Daily [30]
E: Adivet
F: Hämmerle [31]
G: Koshimizu and Lee [32]

Ebrad, Mayor of Mexico City, "Congresso Mundial del Azoteas Verdes", October 7s. 2010) (Tanya Müller and Amenamex personal communication).

In Asia, Singapore started a green roof policy to promote roof gardens in the1980s. Since about 2002, it has been part of national environmental policy to set up and test extensive green roofs. A special department, called CUGE was founded to promote all types of environmental friendly building and construction technologies [26].

The other mega cities in Asia are also getting on board. Hong Kong has conducted a city-wide study, which reviewed the potential of the technology [27]. Bangkok is just starting with an academic research group and demonstration roofs. All these cities already have roof gardens for recreational purposes. The newer ones integrate rainwater retention technology.

Seoul, in South Korea, is an example of an Asian city which adapted the idea of "Biotope area factor" from Berlin http://www.stadtentwicklung.berlin.de/umwelt/landschaftsplanung/bff/index_en.shtml). A green roof with a growing media more than 90 cm has a thermal insulation value of 0.7, a green roof with more than 20 cm has 0.6, and a green roof less than 20 cm has 0.5. Also, a planted wall has a value of 0.4. By 2012, the city hopes to vegetate 600 roofs. Fifty percent of the costs are borne by the state. In 2009, more than 300 green roofs have been installed equaling 100,000 m^2 in total. The Women's University in Seoul is a beacon and a prime example of Seoul's earth-covered buildings [28].

Japan supports green roof projects in about 50 cities. Tokyo, for example, provides a tax break of 50% for 5 years after the installation. New buildings larger than 1,000 m^2 must be offset with at least 20% vegetated surface, which can include the roof surface. There is no general guideline for all Japanese cities [29] (Figs. 2 and 3).

Green roof advocates and activists can be found in nearly every Australian city. They organize workshops and seminars. One of the most prestigious projects using green roof technologies in Australia is on the house of Parliament, in Canberra. It was designed in the late 1970s with a Kentucky blue grass turf roof and many roof gardens, for recreational space for employees. In Sydney, green roof regulations were first instituted in 2008. Other Australian cities are following suit. Main issues in Australia are roof gardens, native plants, and "food on the roofs." The idea of green roofs and water savings, as well the question to accept dried out vegetation during droughts is on the very beginning.

It is not easy to provide an overview of African activities. There are ancient green roofs in many African countries, like Tanzania and Uganda. Modern projects are beginning to be seen in South Africa, especially at holiday resorts and fashion retail stores.

In summary, there are examples of green roofs in more than 40 countries worldwide. An interest on the ecological benefits of roof greening is growing. Establishing regulations that focus on the main needs of each country will be the next major challenge for local environmentalists.

Longevity of Green Roofs

The reason green roofs last longer than traditional roofs is the additional layering, which blocks direct exposure to solar radiation Solar exposure causes premature aging of unprotected roof membranes.

The simplest explanation for this benefit is the direct comparison of roof surface temperatures during daytime. Temperatures up to 70°C are possible on a roof that has not been greened. Temperatures are reduced on the green roof surface because of the shading that the vegetation layer provides as well as evaporation cooling. On summer nights, the surfaces of black tar roofs are often cooler than green roofs. These extreme temperature ranges experienced by a nonvegetated roof are another reason for their premature aging.

What these effects mean for a building's energy budget depends on the amount of insulation and the thermal flow through the entire roof construction. This can be calculated for the purpose of assessing energy savings. In both hot and cold countries, the thermal insulation properties of green roofs are an important benefit. It can equate to a significant reduction in building energy requirements. Calculations using a data set from a Neubrandenburg roof for 1 year [33] showed that about 100 m^3 less heating gas would be required for a single house with normal insulation when a green roof has been installed.

In terms of cooling, impressive thermal insulation properties have been observed in two studies conducted by the National Metsovio University of

Green Roof Infrastructures in Urban Areas. Figure 2
The grass roof on the Parliament house in Canberra is an semi-extensive green roof, Australia

Green Roof Infrastructures in Urban Areas. Figure 3
Intensive Green roof, one of the roof garden areas for the Australian politicians in the House of Parliament

Athens. They studied the thermodynamics of the oikostegi green roof installed on the Treasury in Constitution Square, in Athens, opposite the Greek Parliament. They found that total annual heating and cooling energy savings equaled nearly €6,000. They made a number of important observations, which can be summed up by their conclusion "the thermodynamic behavior of the Greek Treasury is being significantly impacted by the oikostegi green roof."

The amount of captured and evaporated water is also an important aspect for determining reductions in summer air conditioning that could be attributed to green roofs. Of course, it is unwise to use savings in energy consumption to irrigate a roof because water is an even more fundamental and important finite resource than energy. Depending on the region, cooling requirement reductions could be more important than heating requirements. The Metsovio Study suggested that it is feasible to approach a reduction of up to 100% in air-conditioning requirements in a building where an oikostegi green roof has been installed.

How to Promote the Idea of "Green Envelopes"

In order to convince clients to install green roofs, practitioners must explain the technology and create demonstration projects to give them a sense of how these structures will look. To convince economists and legislators, it is important to quantify the economic costs and benefits of green roofs. Most cities start first with incentive programs, for example, the City of Linz (Austria) set up financial support for green projects for a couple of years. Then, after this worked well, they reduced the amount of money provided. Once the technology was established, it took off by itself [34].

In contrast with planting back yards and walls with climbing plants, green roofing technology needs more professional designers and technicians to avoid the potential of waterproofing compromise and other damage to the underlying roofing and construction materials. Berlin has had a long-term program from 1983 to 1994 [13] to incentivize more greenery in the city. This underlying requirement for a professional orientation for green roofs may explain why 466,571 m^2 green backyards have been constructed but only about 63,575 m^2 green roofs.

US Green Roof Policy There is incentive legislation in many US cities, like Washington DC, Boston, Baltimore, Portland, and others [35]. The environmental protection agency (EPA) set up state policy programs to support green roofing. One of the earliest of such, in September 2007, focused on the reduction of the storm water runoff using green roofs. The next steps will be to consolidate these steps and enhance the reach of the legislation to include other benefits such as thermal insulation. Policy programs are fundamental, but these should be supported by demonstration projects which are then studied by independent academic research organizations who can quantify the benefits of green roofs. Many American projects are documented by the proud activists who post their activities on the YouTube internet platform. Nearly 3,000 contributions are posted under the title "Green roofs"; the majority of these are from the USA (improved in January 2010). The German term, "Gründächer" only got two hits. This is a mirror of an expanding environmental awareness in the USA. Knowledge of this may help to reinvigorate the green movement in Europe.

One important benefit of green roofs is the reduction of storm water runoff, which has been documented in Europe for nearly 20 years by several research institutes. Similar studies are now underway in about ten different institutions in the USA such as PennState, and the Lady Bird Johnston Wildflower Center in Austin, Texas. In 2006, the US mayors' assembly passed a green roof resolution at their annual meeting, at which they stated that "green roofs manage storm water naturally, reduce flooding risk and improves air and water quality." For only a little extra cost during roof installation, long-term benefits can be achieved.

Green Roof Growing Media and Plant Species Richness

A green roof begins on the final surface provided by the builder whether that be metal, wood, or concrete. The first layer and one of the most fundamental aspects of a green roof is the waterproofing. There are a number of ways that sound waterproofing can be achieved, and this variation is due to different building conditions and codes in different countries. For example, in Germany, where building codes are very strict, resulting in highly homogenous final roof surfaces, it is common to find single ply PVC membranes being used. In other less developed countries, such waterproofing technologies are not viable and other forms of waterproofing must be tested, proven, and then used. One thing is certain; there must been good communication between the waterproofing industry and the green roof industry to ensure the quality and viability of green roofs. Guarantees must be provided by the water proofer to the client.

Basic Technical Components are Explained in Fig. 1

Growing media choice can affect the roof's water holding capacity, drainage, and nutrient supply. Nutrient availability is higher for roof garden soils than for extensive roof substrates.

For extensive green roofs, some substrate characteristics have been defined:

Suitable materials are lava aggregates between 2 and 16 mm, pumice, expanded clay, crushed bricks or tiles, basalt gravel, tuff gravel, or gravel.

Growing media criteria have also been described. Good water-holding capacity is defined as more than 45%/volume, pH values should be between 6.0 and 8.5, and the organic matter content should be lower than 90.0 g/l, [1].

Growing media should be mixed locally, in order to achieve regional characteristics and meet production standards. Each of the different substrate brands have their own trade secrets for finding the best mixture within the material framework described above. Delivering the same quality substrates repeatedly is a must for professional producers of growing media. New mixtures must be tested by certified laboratories. There are testing facilities, where studies analogous to the German testing procedures are conducted, in the USA as well. Growing media for different regions must be engineered to specific local requirements.

Various planting techniques are possible. Seeding is possible, if no danger of erosion exists. Dispersing cuttings and shoots of Sedum is a very effective and cost-effective method. For ornamental plantings, mini planters are suitable products. Preproduced turf mats are a well-tested option used in Germany since the 1980s. Similar technologies will be established in the USA and some other countries. Quality criteria for roof plants in Germany follows standards developed by the FLL in Germany and also follow German DIN (Deutschland Industry Norma) standards such as DIN 18916.

If green roofs are to be installed for specific purposes, such as in natural conservation areas where native plants are wanted, more sophisticated standards must be applied.

Suitable vegetation should be selected according to the type and depth of growing media. On shallow layers up to 15 cm in all climates, drought-adapted plant species are the best choice. Succulents are a favorite group in the Northern Hemisphere [36]. Also, in hot humid tropics some succulents, originally from the South African cape region perform well on extensive green roof structures [37]. The reason for this is that these areas may also experience prolonged drought [38]. Xeric gardens with cacti are good choices in the tropics for saving irrigation water. The concept of xeric roof gardens would be choice for dry adapted plant species and an ecological protection layer for the building [39]. The old green roofs in Europe were planted with a type of xeric garden. Environmental education is needed to reeducate the public to understand and appreciate the natural beauty of dry gardens. A public that has come to consider manicured English highly maintained lawn to be the ultimate in visual appeal without realising the obscene damages by the high input of fertilizer and pesticide to the urban ecosystem causes. Dry green roofs like the Greek oikostegi perform well from the view point of energy savings and rainwater retention as already stated.

The genus Sedum is the favorite for many extensive green roof versions. Sedum can survive long periods of drought. In temperate climates, Sedum album is a species that can exist on nearly no growing media. If the roof has a little shade, Sedum album can cover the full roof area. The genus Sedum has representatives in various regions of the Northern Hemisphere (Clausen). Furthermore, many cultivars exist and add to the local flora. There are over 600 species of Sedum growing naturally in every climate on earth. Consequently, Sedum is an ideally suited green roof plant (Figs. 4–7).

Extensive green roofs can be an extension of the surrounding natural ecosystem using endemic local plants. Variation in the depth of the growing media

Green Roof Infrastructures in Urban Areas. Figure 4
Sedum album and other Sedum species on the green roof research

Green Roof Infrastructures in Urban Areas. Figure 5
A well-developed multispecies extensive green roof (Neubrandenburg)

Green Roof Infrastructures in Urban Areas. Figure 6
Arial view of an ecological neighborhood, all with extensive green roofs, near the lake Constance

Green Roof Infrastructures in Urban Areas. Figure 7
Ecological neighborhood Huckstorf near Rostock with about 50 single and double houses. This is one example of about 180 documented existing ecological settlements in Germany (more: http://www.oekosiedlungen.de/)

and different types of growing media can be the foundation for a high diversity of plant species and other organisms (Table 3). In order to support plant species which are less competitive, specific maintenance to keep some space on the green roof open is required. Vegetated roofs can also be designed for the specific purposes of some key species of natural flora or fauna [41]. The bird Black redstart is such a key organism for the green roof movement in London. These birds, whose habitat is threatened by urban encroachment, need more habitats to survive and thrive. So-called brown roofs mimic natural environments and provide viable habitat for such birds [42]. Supporting wildlife with specifically designed green roofs is a way to reduce the destructive impact of new developments that encroach on natural habitats.

Green Roofs as Green Corridors in Urban Areas

Green roofs, living walls and back and front yard gardens can become corridors in cities providing pathways of biodiversity. Such green belt systems connect different open urban spaces for plant species and urban animals. The quantity and the quality of these areas should be assessed and modeled in order to enhance future efforts in this direction. In Germany, sites are assigned scores which are called "Biotope area factor" in Berlin or KÖH value in Karlsruhe. In Germany, these scores are the basis for assessing property value and so they are also used to assess measures that can be taken to improve the quality of life in cities.

In Germany, green roofs have become so popular that the percentage of a city that has been greened now can be calculated rather than just talk about the square meter age. Of course, there is still plenty of room for even more green roofs. The popularization of roof greening in Germany has been achieved in large part due to carrot and stick legislation and incorporation of green roof technology into building codes in much of the country. In Germany, about two third of all building permits are only given when a green roof is included in the application. The German Association of green buildings (www.FBB.de) has conducted three surveys concerning green roof penetration of all German Cities larger than 10,000 inhabitants. Summarized results of these studies are available [43].

Green Roof Infrastructures in Urban Areas. Table 3
Types on vegetation and growing media depth

Depth	Type of vegetation	Description
Lower than 5 cm	Mosses, few annual herbs	In most climate regions, this is not enough growing media for a full plant cover
5–15 cm	Typical depth of a green roof growing media	Within this depth, various plant species are suitable, up to 10 cm in most parts of Europe; Sedum and some herbs are the winners. With more than 10 cm depth grass vegetation dominates [40]
15–50 cm	Suitable for turf, herbs, and shrubs	This is the depth suitable for a wide range of ornamental plant species with irrigation. Without irrigation, several herbs and grasses can survive for a long time.
More than 50 cm	Shrubs, small trees	More than 50 cm with irrigation can support shrub and tree vegetation

Future Direction: A Simulation of Potential Green Roof Benefits to Urban Areas

Each green roof is unique, but new projects can benefit from well-documented existing ones. Detailed documentation, as a case study of a retrofit project, has been prepared for the green roof on the ASLA headquarters in Washington DC [44]. This project includes roof gardens and extensive green roofs. The project is being monitored to assess the benefits of the installation. This example could be applied around the world. Due to technological advancements, green roofs are now suitable and viable for both retrofit and new buildings [45].

To achieve city-wide benefits, many green roofs must be erected. The potential impact of green roofs on urban environments has been described for Toronto, in a sophisticated study. The aim of the study was to ascertain what the benefits would be derived if all roofs larger than 350 m^2 were greened in Toronto (about 500 ha). The study found that such a move would result in savings of C$46,000,000 from storm water amelioration alone. Annually, cost savings of avoiding beach closures were about C$755,000. An annual reduction in air-conditioning requirements during the summer equaled C$12,000,000 [22]. This equals an air-conditioning requirement reduction of 2.37 kWh/ m^2 year.

The benefits of green roofs for New York have been modeled [46] by measurements of the PennState University. This study suggested that significant reductions in heating requirements particularly during the night would result from the installation of green roofs. Also, the study found similar runoff amelioration benefits to Toronto. These two benefits are driving the implementation of green roofs in NYC. Another oft overlooked benefit of the storm water runoff amelioration impact of green roofs is that smaller bore sewage systems can be used meaning substantial economies to local authorities as they rebuild decaying infrastructure. Many other city authorities are developing a healthy interest in green roof research. For instance Seattle, Vancouver, and Washington are all investigating the benefits of green roofs. Rain harvesting potentials of green roofs is another area of interest to local authorities [47, 48].

A combination of green roof technology with other instruments such as living walls using climbers and other technologies opens a wide range of possibilities for greening in Cities [49].

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Recommended and Selected Internet Links

www.worldgreenroof.org
www.greenroofs.org
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www.greenroofs.com
http://www.epa.gov/npdes/pubs/gi_supportstatement.pdf
http://www.usmayors.org/urbanwater/policyres_06c.asp
http://www.ecos.org/content/policy/detail/2861/
http://cfpub.epa.gov/npdes/home.cfm?program_id=298
http://greenvalues.cnt.org/calculator
http://freitext.ub.tu-berlin.de/gartenkunst.html (garden historic documentation on older Green roofs in Journals of the 1920th)
http://www.oekosiedlungen.de/
http://www.oikosteges.gr

Green Roof Planning in Urban Areas

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Article Outline

Definition of the Subject and Its Importance

Green roofs are vegetated substrate layers on top of the waterproof membrane of the conventional roof surfaces of buildings. Once the concern that plants could negatively affect plants was overcome, by the use of improved membrane layers that are protected from root penetration, green roofs became more popular, starting in the late 1970s in Germany, Austria, and Switzerland.

As the twenty-first century has been deemed by the UN as the century of the megacity with predictions that nearly 75% (?) of the population of the world will live in cities by the end of the century, urban areas will increasingly need to be planned and developed to take into consideration the ecological and environmental health of the urban climate to ensure cities can cater for people. This is also a pressing matter in as it is recognized that there is a need to adapt cities to the negative effects of climate change. These issues have been central to the work of professionals in the field of green roofs over the last 20 years and increasingly the technologies and approaches of green roofs have been shown to have a positive effect on a number of issues facing cities and mega-cities in terms of ecological and environmental health and in helping cities adapt to climate change, reduction of the urban heat island effect, reduction in localized flash floods, air and noise pollution and increasing biodiversity in the urban realm. These processes are part of an evolving approach to planning referred variously as green infrastructure or ecosystem services. Urban greening has therefore become an increasingly important approach for planners and is likely to be the one that will predominate in the future.

The Swiss architect Le Corbusier set the installation of green roofs in the form of roof gardens, as one of his five principal requirements in establishing a new architecture in the early twentieth century (Busse 2000). Although his work became well known, it took a long time after Le Corbusier's first steps to the implementation of green roofs as an ecological measure to be absorbed into mainstream urban planning. Green roofs became more popular as a part of ecological construction in the 1970s, and in the early 1980s, a number of cities implemented nascent strategic planning approaches to encourage the uptake of green roofs. Elsewhere a series of pilot projects were initiated to explore the ideas and approaches to green roofs in urban areas. The main drivers for the implementation of green roofs in the 1970s' and 1980s' research also suggested that green roof provided a broad range of environmental benefits, such as energy savings (less winter heating), reduction in storm water runoff, and overheating, but there was also a recognition that green roofs also promoted health and well-being and were an essentially element in an "ecological" approach to construction.

Introduction

Green roofs are vegetated layers that sit on top of the conventional roof surfaces of a building. Usually a distinction is made between "extensive" and "intensive." These terms refer to the degree of maintenance the roofs require. Intensive green roofs are composed of relatively deep substrates and can therefore support a wide range of plant types: trees and shrubs as well as perennials, grasses, and annuals. As a result, they are generally heavy and require specific support from the building. Intensive green roofs (what most people think of as roof gardens) have in the past been rather traditional in their design, simply reproducing what tends to be found on the ground, with lawns, flower

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beds, and water features. However, more contemporary intensive green roofs can be visually and environmentally exciting, integrating water management systems that process waste water from the building as well as storing surplus rainwater in constructed wetlands. Because of their larger plant material and horticultural diversity, intensive green roofs can require substantial input of maintenance resources – the usual pruning, clipping, watering, and weeding as well as irrigation and fertilization.

Conversely, the green roofs that have received the greatest interest recently are extensive green roofs. They are composed of lightweight layers of free-draining material that support low-growing, tough drought-resistant vegetation. Generally the depth of growing medium is from a few centimeters up to a maximum of around 10 cm. These roof types have great potential for wide application because, being lightweight, they require little or no additional structural support from the building, and because the vegetation is adapted to the extreme roof top environment (high winds, hot sun, drought, and winter cold), they require little in the way of maintenance and resource inputs. Extensive green roofs can be designed into new buildings, or "retrofitted" onto existing buildings.

The Headline Benefits of Green Roofs to Urban Planning and Climate Change Adaptation

Green roofs provide a range of benefits to urban areas. However, there is an increasing interest in three particular headline benefits, namely, amelioration of the urban heat island effect [UHIE]/thermal performance of buildings, reduction in stormwater flows, and providing habitat for wildlife in cities.

The first two are particularly relevant in terms of climate change as there is a recognition especially in temperate and Mediterranean climates that climate change is likely to increase summer temperatures in cities, thus increasing the negative effects of the UHIE (and potential increase in death caused by heat excess) and an increase in the need for air-conditioning (and therefore increase in energy/carbon use). The other prediction is that climate change will lead to increase in intense summer storms leading to flooding in urban areas with a negative effect on both the ecological and economic conditions within urban areas. In many cities, these predictions are actually happening already. Therefore, there is a pressing need to adapt urban areas to ameliorate both effects and thus ensure the ongoing ecological health and economic well-being of urban areas.

Urban Heat Island and Climate Change Adaption

The benefits green roofs can bring in terms of climate change adaptation can be significant, especially in terms of the urban heat island effect and the energy balance of a given building.

Conventional roofing surfaces, including recreational roofs, absorb sunlight and heat up quickly. The absorption of radiation and the release of the radiation back to the atmosphere during the night is a major factor in UHIE. Where a building has poor insulation and poor ventilation, this can lead to increased use of air-conditioning and therefore increased energy use [1].

Building Energy Balance

The use of vegetation on the roof surface ameliorates the negative effects of conventional roofing surfaces by absorbing heat and using this heat in evapotranspiration. The process of evapotranspiration is an important element in reducing UHIE and provides benefit to the individual building by cooling/insulating the spaces beneath the roof.

Studies have shown that the membrane temperature beneath a green roof can be significantly lower than where the membrane is exposed. Table 1 shows the average temperatures under the membrane of a conventional roof and that of membrane under green roofs in a study undertaken at Nottingham Trent University.

Green Roof Planning in Urban Areas. Table 1 Study of temperatures under membranes of a conventional and a green roof

	Winter	Summer
Mean temperature	0°C	18.4°C
Temperature under membrane of conventional roof	0.2°C	32°C
Temperature under membrane of green roof	4.7°C	17.1°C

www.greenroofs.co.uk

Another study in Ottawa, Canada, by the National Research Council of Canada noted that temperature fluctuations during spring and summer on a conventional green roof were of the order of 45°C while under a green roof the fluctuations were in the order of 6°C [6].

The positive effect on the temperature of the membrane under a green roof not only protects the membrane from the effects of UV, frost, and sunlight, but also moderates the heat flow through a building by shading, insulation, evapotranspiration, and thermal mass.

Urban Heat Island Effect and Indirect Energy Savings

- "Summers by 2050 will be 1.5–3.5°C hotter. . .in central London the urban heat island currently adds 5–6°C to summer night time temperatures and will intensify in the future." *London's Warming. The Impacts of Climate Change on London* www.london.gov.uk

Urban areas have a higher average temperature than surrounding rural areas; this difference in temperatures is called the urban heat-island effect. An increase in the UHIE is likely to lead to increased air pollution and increased use of air-conditioning.

As has been noted already that green roofs do not store heat like conventional roof surfaces but dissipate heat through evapotranspiration. Such a process can have a significant effect on helping to reduce the impact of the UHIE.

A modeling scenario undertaken in New York by the New York Heat Island Initiative determined that providing 50% green roof cover within the metropolitan area would lead to an average 0.1–0.8°C reduction in surface temperatures. It is noted that for every degree reduction in the UHIE roughly 495 million Kilo Watt hour of energy would be saved. The same study also looked at various mitigation strategies other than green roofs, including urban forestry and cool roofs and noted that "living roofs" provided greater benefits than white or "cool" roofs. It was clear from the study that a combination of various mitigation strategies for UHIE including green roofs should be considered by the city. http://ccsr.columbia.edu/cig/greenroofs/index.html www.nyserda.org/programs/environment/emep/project/6681_25/6681_25_project_update.pdf

A study in Toronto estimated that there are 50 million square meters of potential roof space in the city of Toronto that could be greened. Overall it was estimated that the effect of greening the city's roof tops would lead to 0.5–2°C decrease in the UHIE.

A reduction of this magnitude would, the study estimated, lead to indirect energy savings citywide from reduced energy for cooling of $12 million, equivalent to 2.37 kWh/m^2 per year [0.001 CO_2 emissions t/m^2]. http://www.toronto.ca/greenroofs/findings.htm

Energy Savings

Although green roofs do provide potential energy savings by providing building insulation these are often considered difficult to assess due to the varying climatic conditions throughout the winter months, and will be minimal on already well-insulated buildings. However, during summer months, green roofs can have a significant effect on spaces beneath them in terms of cooling.

Studies in Germany have provided various estimates. Figures provided by Zinco estimate that 2 L of fuel oil are saved per square meters per year. A more recent published study on domestic buildings with flat roofs suggests that there is a 3–10% winter saving on fuel bills. The results of the study suggest that there is a maximum saving of 6.8 kWh/m^2 [calculated CO_2 emission tones saving of 1.5 kg/m^2] and a minimum saving of 2.0 kWh/m^2 [calculated CO_2 emission tones saving of 0.44 kg/m^2]. This study did not consider at any summer savings due to cooling [5].

The Toronto study, already referred to above, estimated that the direct energy savings citywide as a consequence of whole scale greening through reduced energy for cooling would be in the order $22 million, equivalent to 4.15 KWh/m^2 per year [0.001 CO_2 emissions t/m^2]. The study also concluded that there would be a reduction in peak demand in the order of 114.6 MW, leading to fossil fuel reductions in the region of 56,300 metric tons per year.

The only information for a building in London suggests that an 850 m^2 retrofitted green roof onto paving in Canary Wharf has seen an estimated reduction of 25,920 kWh in a year, through a reduction in heating and cooling of the spaces below the roof *[per com Livingroofs.org]*.

Green Roofs and Photovoltaic Solar Panels

The combination of green roofs and PV Solar Panels provide multiple benefits. Photovoltaic panels at roof level are known to work more efficiently when installed on a green roof rather than a conventional surface. The green roof element not only saves energy during the summer time [see above] but can increase efficiency of PV by reducing fluctuation of temperatures at roof level and by maintaining a more efficient microclimate around the PV panels. The performance of photovoltaic panels is lowered by 0.5% per °C above or below 25°C. The green roof is better at maintaining the ambient temperature of 25°C [3].

By reducing the temperatures around the PV and by helping reduce the need for air-conditioning in spaces beneath the green roof, the combination of the technologies should be as one of positive interaction and not one of competition in terms of use of roof space [4].

Benefit of Green Roofs to Stormwater Runoff, Flash Floods, and Pollution Removal

Background The combined impact of ongoing development within urban areas and climate change has created higher peak stormwater flows, leading to an increased occurrence of downstream flooding and pollution. Intensive summer storms are becoming, and are likely to become, more prevalent. Such rainfall events, especially in the summertime in temperate zones, can cause the current stormwater system to become overburdened causing localized flooding. The consequence of these events can have both a negative economic and ecological effect. For example a "freak" summer storm in 2005 in West London deposited such a large amount of rainwater that caused raw sewage to be released into the River Thames. This pollution caused large-scale ecological damage to the river's ecosystem, including significant fish mortality. Another series of summer storms in July 2009 in London led to closure of parts of the transport system within the capital causing offices, shops, and businesses to be closed and a reduction in trade/business.

In many parts of the world, sustainable drainage systems (SUDS) are now required to minimize the impact of both new and existing development. They are designed to both manage the adverse environmental consequences resulting from urban stormwater runoff and also contribute to environmental enhancement wherever possible. The use of green roofs can provide a pivotal role in achieving this as they successfully achieve source control, which is the fundamental concept of SUDS, i.e., the control of rainfall at or as close as possible to its source.

Positive Effect of Green Roofs on Runoff Rates and Volumes of Stormwater

Around 30–40% of rainfall events are sufficiently small that there is no measurable runoff taking place from greenfield areas (it all infiltrates or evaporates). In contrast, runoff from developed areas takes place for virtually every rainfall event. This means that streams and rivers are more subject to overload. In addition, whereas for greenfield areas, small events would be treated through natural filtration processes, development runoff can flush surface pollutants directly into the receiving waters. Where it is possible to provide replication of this natural behavior (described as interception storage) and to prevent runoff of up to 5 mm, this should be provided.

By using green roofs as a source control technique, the volume of surface or underground attenuation storage can be reduced considerably. This can be particularly important in dense urban developments where space for surface level SUDS components such as ponds will be limited. It is also an important consideration when looking at the true cost implications of installing a green roof as the reduction in underground drainage infrastructure must be taken into account as well as the reduced number of downpipes and smaller pipe network, etc.

When rain falls on a green roof, it will first pass into the substrate and possibly pass through until the adsorbancy of the soil is activated (although throughflow will generally be low). It is then absorbed by the substrate (and possibly the drainage layer) and taken up by plants in the same manner as a greenfield site.

For most small storms the rainfall is removed by evapotranspiration. Only when the soil is fully saturated will water percolate through to the underlying drainage layer in significant volumes.

The processes involved in the operation of a green roof are (Tarr 2002):

- Retention of rainwater in substrate and drainage layers
- Uptake of water and release by plants as vapor (transpiration)
- Uptake of water and biochemical incorporation by plants (photosynthesis)
- Evaporation from substrate due to wind and sun

There is a wealth of published information that demonstrates the performance of green roofs in attenuating stormwater runoff by reducing peak flow rates and volumes.

Although there is a variation in performance depending on rainfall patterns, this is no different to other SUDS components such as pervious pavements, or indeed greenfield catchments.

The benefits of a green roof in terms of drainage can be summarized as follows:

1. A green roof will typically intercept the first 5 mm and more of rainfall (provide interception storage).
2. The amount of stormwater stored and evaporated is primarily dependent upon the depth of the growing medium and type of planting. In the summer, a green roof can typically retain between 70% and 80% of the runoff (Livingroofs.org 2004).
3. It has been demonstrated that in Germany between 40% and 100% of rainfall can be retained – depending upon the season (Tarr 2002).
4. Seventy-five percent of rain falling on extensive green roofs can be retained in the short term and up to 20% can be retained for up to 2 months (English Nature 2003).
5. As the rainfall events become longer or more intense, the positive effect of a green roof remains as there is still a significant reduction in peak runoff rates. This increase in the "time of concentration" means that a green roof will be beneficial throughout a wide range of rainfall conditions [2].
6. The above benefits collectively mean that by incorporating a green roof into new development, there will be a reduction in the amount and cost of the overall drainage infrastructure required to serve that development.

Green Roofs and Pollution Removal from Stormwater Runoff

Green roofs retain, bind, and treat contaminants which are introduced to the surface either as dust or suspended/dissolved in rainwater.

The London Ecology Unit (1993) stated that 95% of heavy metals are removed from runoff by green roofs and nitrogen levels can also be reduced. In addition, Auckland Regional Council (2003) advise that green roofs are accepted as removing 75% of total suspended solids.

The roofs showed a reduction in nitrogen (total discharge from green roofs of between 10 and 80 mg/m^3 during the monitoring period) and phosphate was also removed from the runoff (total discharge of between 75 and 100 mg/m^3). The total discharges of nitrogen and phosphate from the conventional roof were 265 and 145 mg/m^3, respectively.

Role in Urban Planning

Examples from

London During the late 1990s, a group of nature conservationists and ecologists were actively in involved in a major regeneration program in South-East London. The Creekside Regeneration Programme was a government-funded program to rejuvenate an economically deprived area of Deptford in the London Boroughs of Lewisham and Greenwich. Part of the preparatory works included an ecological assessment of the value of the area for wildlife. Although a rundown postindustrial landscape the group discovered that, although not the most visually appealing landscape there were a number of interesting species, including one – the black redstart (*Phoenicurus ochruros*), which were of significant ecological value.

Although the use of green roof technology had been tentatively used in the 1970s and a number of innovators had tried to raise the profile of the technology through example projects and a book published by the London Ecology Unit [Building Green], the technology had remained relatively marginal.

However, the work of the group in Deptford pushed developers and planners to consider the use of green roofs as mitigation for wildlife habitat, especially for the aforementioned bird. However, with little information on the value or the technical aspects of green roofs, the process was a hard task. Convincing the relevant professionals, architects, consultants, and planners that this was both technically and an ecologically sound method of roofing was an uphill struggle. In effect, the group was on a process of change, changing people's habitats and assumptions and professional attitudes to vegetation on buildings. Fortunately, in early 2000, the author contacted the Swiss Landscape Department, which led to the first contact with Dr. Stephan Brenneisen and his innovative work on green roofs and biodiversity.

Thus was born the UK+CH green roof partnership. Although the Swiss regulatory process and attitude to green roofs was on a different level at the time, being one of proactive engagement, the Swiss experience has been a major influence on bringing green roofs into the mainstream in London and elsewhere in the UK. The relationship has been one of the major influences in transforming green roofs from a fringe sustainable technology to one that is now incorporated in both strategic policy in London, both at the regional and the local level. Although the agenda for green roofs as moved forward from an initial interest in biodiversity and nature conservation issues, to other themes, such as thermal performance, urban heat island amelioration, and sustainable urban drainage, at its heart the provision of quality green roof habitat for rare invertebrates and birds still remains, and is still a major driver in terms of implementation.

The Black Redstart Although relatively common on the continent and especially in Switzerland, this bird is at the northwesterly edge of its range in the UK. As it is a relatively recent addition to the UK bird fauna, it is vulnerable to competition from more established species, such as the Robin (*Erithacus rubecula*). With less than 100 pairs annually thought to breed in the UK, it is therefore protected under national wildlife legislation. It is relatively unique for a UK protected species as it is found in the main on industrial wastelands and in an urban context. It needs quite sparsely vegetated landscapes, similar to alpine scree slopes and plateaus.

In 1997, a group of ecologists found a number of pairs breeding along Deptford Creek. As the three pairs that were found in the area constitute more than 1% of the national population, there was a degree of pressure, through planning regulation, to ensure development did not have a negative impact on the species. Wherever possible there is an obligation to "enhance or mitigate" development plans for protected species. Thus was born a move to ensure that new developments catered for the black redstart. One of the first projects to be impacted on was the Laban Dance Centre, designed Herzog de Meuron.

The "rubble" roof was the first of many green roofs installed for black redstarts in London. Thirteen years ago this was a real milestone. But now, after much work, green roofs for biodiversity have become embedded.

However, the nature conservationists involved in promoting green roofs had very little knowledge or understanding of the know-how and the technical arguments to pressure developers to deliver habitat at roof level. Most of their thinking was intuitive. Furthermore many professional ecologists viewed the "idea" as unfounded and lacking in any hard and fast data to back up the intuitive reasoning of group. The Swiss connection would change that providing a greater technical understanding of green roofs supported by detailed research.

The Ecological Context While the black redstart started was the starting point for a renaissance in interest in green roofs in London and increasingly across the rest of the UK, a further issue raised its head with the publication of a strategic white paper that set out the vision for development in the UK but which nature conservationists saw as having potentially negative impacts on a swathe of habitats, that, although postindustrial, had become important refuges for a whole swathe of rare and endangered species. In 2000, the UK Government published the Urban White Paper. In the context of this story, the white paper targeted the use of brownfield and postindustrial land as the primary source of land for new development. In London and also in the Thames Gateway Development region, large areas of old factories, dockyards, disused refineries, power stations, and other land become the prime focus for economic regeneration. However, at the same time, these rather ugly and untidy landscapes were increasingly being recognized by urban ecologists as some of the most important sites in the UK for rare invertebrates. Much of this fauna had once been prevalent in well-drained and low-nutrient farmland that had since been improved. In general many postindustrial sites reflect this habitat characteristic. Thus, over time, much of the fauna and flora had colonized these as they were left to nature. In fact one such site in South Essex, Canvey Wick, has been celebrated as "the Amazonian rainforest for rare invertebrates in the UK." Thus was born a conflict between the needs for economic regeneration and an ecology once overlooked but of national importance. At the time of writing a number of other similar sites have become the focus of concern from conservationists, notably the Isle of Grain lorry park (http://www.guardian.co.uk/environment/2011/apr/17/isle-of-grain-wildlife-paradise).

Climate Change: A Shift in Emphasis During the mid-2000s, there was a distinct policy shift as the climate change agenda became more prevalent. Where the London Mayor had previously been concerned with "fuel" poverty a series of extreme hot summers shifted the emphasis to also include concerns regarding "cool" poverty and the likely impacts of increased summer temperatures and the negative effects of the Urban Heat Island. The London Climate Change Partnership stated in 2002 that "Summers by 2050 will be 1.5–3.5°C hotter...in central London the urban heat island currently adds 5–6°C to summer night time temperatures and will intensify in the future" [6].

Thus, green roofs were seen to be a potentially crosscutting technology and multi-beneficial solution that could help the capital meet the challenges of climate change and help the city adapt to the likelihood of higher summer temperatures and increases in intense summer storms [leading to localized flash floods]. These fears have been realized to a certain extent with the exceptionally hot summers of 2005 and 2006 and extensive flash flooding of 2007.

However, London has both a central strategic authority [the Greater London Authority] and also 32 local boroughs [LB] with responsibility for their area. A number of these boroughs, notably city of London, Islington, Lewisham and Tower Hamlets, were actively promoting and ensuring that green roofs were installed for nature conservation.

The New London Plan In 2007, the author, along with colleagues, was commissioned to write a technical review of green roofs and green walls. This report was to support the change in policy on green roofs from one of "encouragement" to "expectation." The report reviewed all the technical data available for a range of benefits including reduction in the urban heat island, thermal performance, storm water attenuation, biodiversity, and amenity. It also reviewed city policies elsewhere in the world. The technical report, published in late 2007, led to a distinct policy on living roofs and walls in the revised London Plan published in March 2008.

The new London Plan Living roofs and wall [Policy statement 4a 11] states:

The Mayor will and the boroughs should expect all major developments to in corporate living roofs and walls, where feasible and reflect this in Local Development Framework policies. It is expected that this will include roof and wall planting that delivers as many of these objectives as possible:

- Accessible roof space
- Adapting and mitigating for climate change
- Sustainable urban drainage
- Enhancing biodiversity
- Improved appearance

Boroughs should also encourage the use of living roofs in smaller developments and extensions where the opportunity arises [5].

Although it is too early to see what the effect of the new policy, green roofs have been delivered on an increasing scale in the capital over the last 8 years and the new Plan should lead to an increase in delivery.

A London Audit Livingroofs.org undertook an audit of green roofs in London in 2004. The total area of green roofs was no doubt underestimated due to the challenges of accessing information from architects, developers, and companies. The audit estimated that 76,682 m^2 of green roofs had been installed in the Greater London area. Some of these roofs dated back to 1932! In 2008, a further audit was undertaken to assess the amount of green roofs installed between January 2004 and December 2008. This used data provided by a number of green roof companies active in the UK and is estimated that the figures provided represent 80% of the roofs installed during that period. Over 420,00 m^2 were installed by the companies suggesting that near to 500,000 m^2 were actually installed – equivalent to twice the size of Hyde Park and Kensington Gardens combined.

It is important to note that the majority of these green roofs were installed in the central core of the city. Furthermore as the table below highlights that the area with the largest percentage of installed green roofs was the London Borough of Islington. This borough had actively promoted the use of green roofs through its planning department, thus demonstrating that urban planning departments that embrace and promote these activities can have immediate effect in the implementation of green roofs.

This area of green roofs installed between 2004 and 2008 was prior to the publication of the New London Plan, and the positive effect of this strategic planning policy on green roof implementation is yet to be assessed but is likely to augment the delivery of green roofs on new developments in the Capital.

A Green Roof Toolkit Although London now has a distinct policy on green roofs and a large number of green roofs have been installed, there has been limited guidance on how green roofs should be installed in London.

The Environment Agency, a key statutory consultee on new developments, is responsible for flood defense and rivers. Its remit covers flooding, climate change, and biodiversity. In 2008, the Thames region of the Environment Agency commissioned the author to provide a detailed toolkit to guide developers to what the Agency expected green roofs to provide and how. Importantly this work also managed to persuade engineers within the Agency to accept that green roofs do provide significant benefits as a source control mechanism in the sustainable urban drainage train [4].

Greening Existing Building Stock With the new London Policy and activities by the 32 LBs, the argument for green roofs on new developments looks positive in the London area. However, one of the key concerns for the London Climate Change Partnership [LCCP] is the need to adapt existing buildings to the challenges of climate change. Reduction of the Urban Heat Island is an important element and, as has been recognized elsewhere, there is a need for a 10% increase in urban green spaces in UK cities to combat climate change. In London, especially in the central activity zone [CAZ] where space is limited and the effects of the Urban Heat Island are most pronounced, roofs will be very important in delivering green space.

The Need to Retrofit The implementation of green roofs in new developments within London is now a mainstream ecological construction method as has been outlined above. However, it is also recognized that there is a need to retrofit green roofs on the existing building stock, especially in CAZ. The report published in 2008 by the London Government estimates that 325 of the land area of Central London consists of roofs that could be retrofit with green roofs in the future without additional structural work to facilitate such an approach. Therefore, the area of roofs within 6 km circle centered on Trafalgar Square that could be greened would constitute a total area of 10million square meters.

The burning issue for planners is how to achieve wholescale retrofitting of green roofs on existing buildings. The London Government commissioned a report, economic incentive schemes, for retrofitting London's existing homes for climate change impacts, which outlines how this might be achieved in terms of incentives and the monies that would be needed to achieve. The report also provided detailed figures on how much such a program would cost and the environmental benefits that it would provide:

- "A scheme for four inner city areas – Cannon Street, Oxford Street, Tottenham Court Road, and Canary Wharf – with a green roof area of 226,750 m^2 would cost around £4 million and provide environmental benefits 17 worth £4 million.
- A wider scheme covering the city of London, part of the London Borough of Hackney, part of the London Borough of Tower Hamlets, and part of the
- A scheme in the West End with a green roof area of 3.2 million square meters would cost around £55.5 million and provide environmental benefits worth £55.5 million" (Table 2).

In a further development since the publication of the report, the idea of retrofitting green infrastructure and in particular green roofs in London is being taken forward by Business Improvement Districts [BID], in particular the Victoria [VBID] area in the South West of the Central Activity Zone. VBID

Green Roof Planning in Urban Areas. Table 2

Area	Potential roof area that could be greened (m^2)	NPV of environmental benefits	Size of scheme
Four inner city areas – Cannon Street, Oxford Street, Tottenham Court Road, and Canary Wharf	226,570	£4 million	£4 million
Four larger sample areas – city of London, part of the London Borough of Hackney, part of the London Borough of Tower Hamlets, and part of the West End	3.2 million	£55.5 million	£55.5 million

Economic incentive schemes for retrofitting London's existing homes for climate change impacts www.london.gov.uk/lccp/publications/docs/lccp-eco-incentives.pdf

commissioned a report and survey of the inner and outer areas that constitute the BID to assess where and what kinds of green infrastructure could be retrofitted. As has been mentioned early, the driving force for the commission was the effects of climate change. The VBID area was one of the key areas affected by flashfloods in the first week of July 2009 with the closure of Victoria Mainline station and VBID recognizes that this led to a significant loss of business within the zone.

The report highlights the issues of flood management within the BID area:

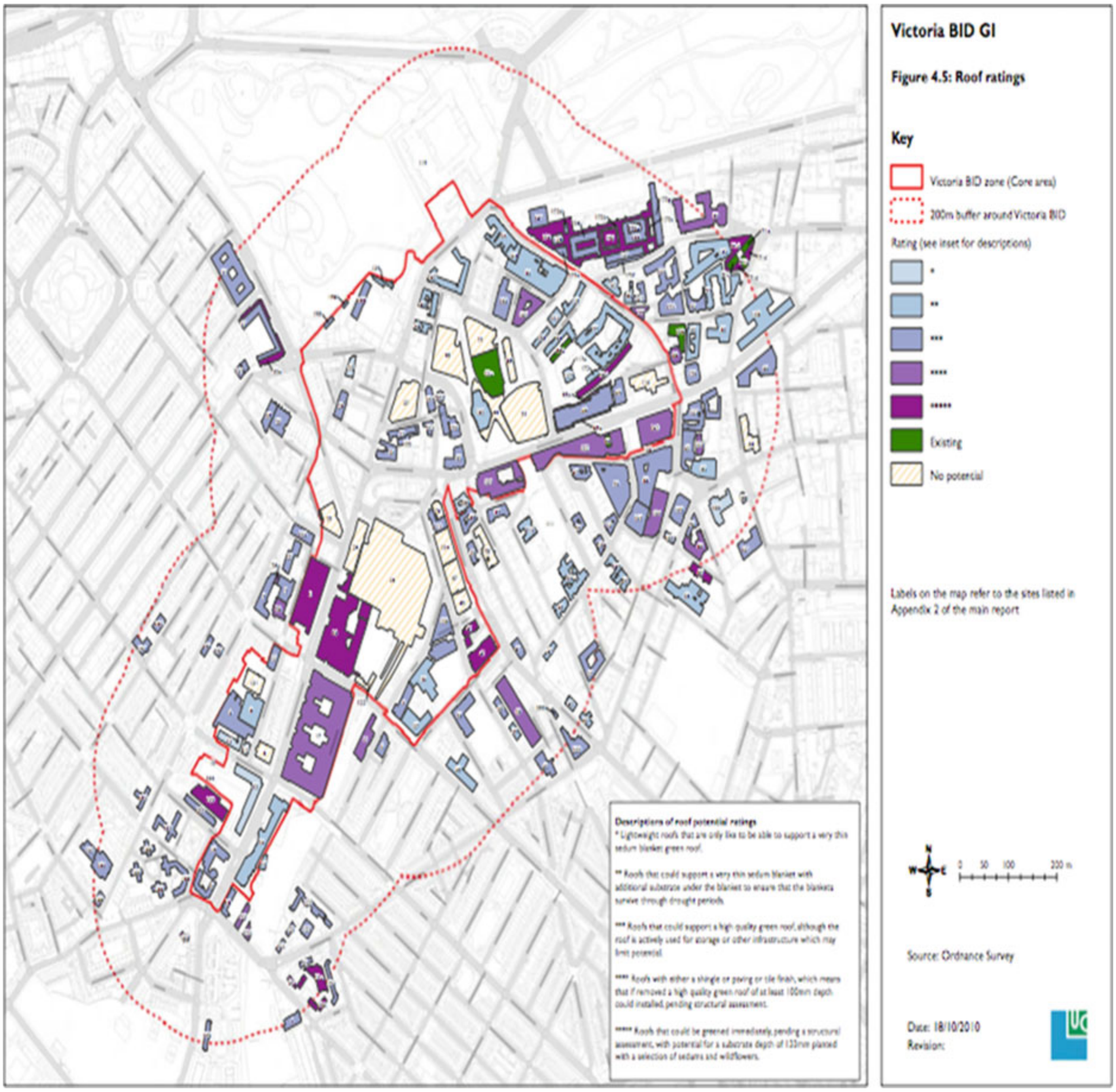
- One of the key environmental challenges in the Victoria BID is the need to reduce instances of flooding at Victoria Station during periods of heavy rain. These instances are likely to become more frequent, and the UK Climate Impacts program predicts that the average winter rainfall could increase by between 12% and 16% by 2050 and by 16–26% by 2080 (UK Climate Impact Projections website, accessed August 2010: http://ukclimateprojections.defra.gov.uk/content/view/2200/499/). Well-designed GI can alleviate the risk of flooding by retaining water.
- Environment Agency data indicates that extensive areas of Westminster are prone to fluvial and tidal flooding, including many parts of Victoria, as shown in Fig. 1. This includes the area directly outside the entrance to Victoria station, and either side of Bressenden Place. Much of the Victoria BID is identified as a Critical Surface Water Flood Location in the recent Westminster Strategic Flood Risk Assessment (SFRA). The SFRA predicts that this surface water flooding will be exacerbated by the predicted effects of climate change, and will affect an even greater area of the Victoria BID. The Westminster SFRA also indicates that a breach of the Thames Barrier would result in flooding which would extend as far as the eastern part of the Victoria BID.

An audit of the roofs was also under and each roof assessed as to whether it could potentially be greened and what type of green roof in terms of depth could be achieved.

The flat roof audit identified approximately 29 hectares of roof area within both the outer and inner cores of VBID area 4.17. Of these 29 hectares of roof, over 25 hectares had the potential to support a living green roof habitat. Of this 25 hectares, 18% had the potential to support a green roof in keeping with guidelines of biodiversity as outlined in the Environment Agency Green roof toolkit, 55% moderate potential and 42% low potential.

Since the publication of the report, other similar audits are being considered elsewhere in London and also beyond the capital in UK.

Both the London Government's report and VBID report demonstrate the commitment in theory to retrofitting green roofs. However the major task will be to ensure that the theory is put into practice. There are now many examples of green roofs that have been retrofitted in London, most of these have been done through either funding streams associated with



Green Roof Planning in Urban Areas. Figure 1

biodiversity or where commercial companies have engaged with Livingroofs.org to specifically deliver seminal projects at their own expense, such as the highest green roof in the UK on top of Barclays Headquarters in Canary Wharf, London. Over the last 4 years a project funded by the SITA NATURE ENHANCED has been ongoing in London. This has led to just under 2,000 m^2 of green roofs being installed on existing buildings throughout the capital for rare invertebrates. One of these projects, 55 Broadway, recently won the Sustain Award for Biodiversity.

A further development that is underway in London is the retrofitting of a number of green roofs as part of the Drain London program (http://www.london.gov.uk/who-runs-london/greater-london-authority/directors-decisions/dd421). The first two will be installed in the summer of 2011. Part of the money allocated for this project is utilized to have the roofs monitored for their positive impact on intense summer storms.

One of the roofs to be funded

The Importance of Policy and refined Planner Tools for green roofs

There is still unfortunately a tendency on designers, whether they be architects or landscape designers, to seek out mechanistic product-based solutions. While most of the

The Future in the UK The development of a unique London green roof policy has been driven by a number of specific factors. Urban ecologists and their issues certainly provided the initial impetus for policy activities and innovations. The climate change agenda and how a large city like London adapts has certainly galvanized the need for a policy. What is needed in the future is a greater understanding and improved planning tools to ensure that good green roofs are installed to meet the cross cutting benefits that a city like London requires. It would be hoped that the Environment Agency Toolkit sets a precedent that at regional level [GLA] and a local [LBs] green roof policies and conditions can be refined to ensure the quality of green roof implementation. There is still unfortunately a tendency on designers, whether they be architects or landscape designers, to seek out mechanistic product-based solutions. While most of the

The implications of green roofs implementation within the capital is having an effect beyond the capital, in particular in the Greater London Watershed – particularly the area known as the Thames Gateway. This area includes much of East London and stretches along the Thames estuary into Kent and Essex. Already there are a number of huge developments, which are under pressure to include green roofs as mitigation and compensation for ecological reasons.

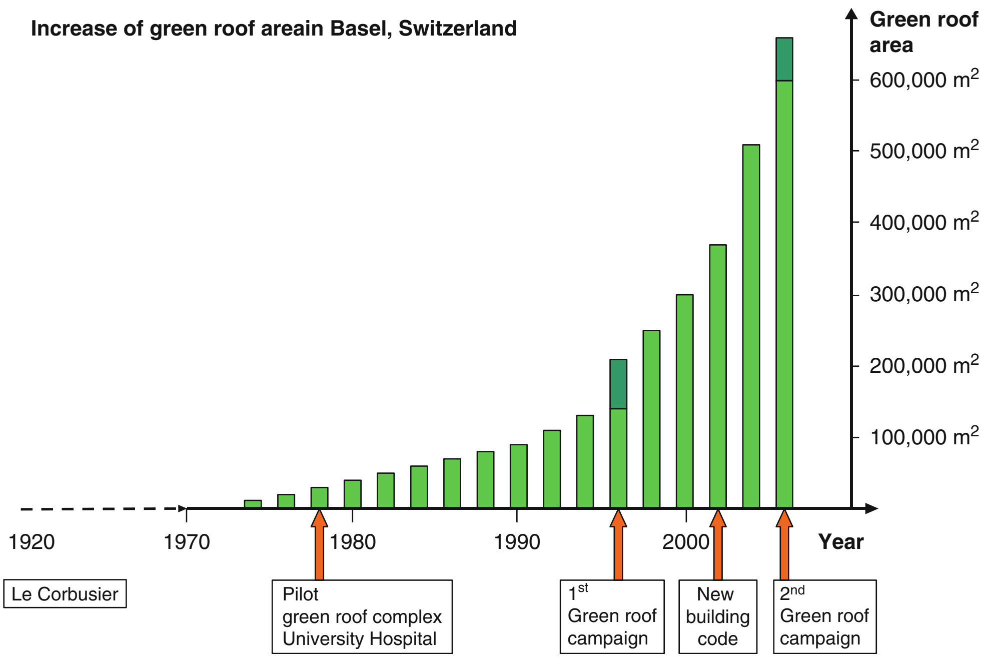
However, there will be a need to constantly refine policy to meet the changing climate and needs of London. Green roofs are certainly no longer a fad but are an ever-growing market and an integral response to impending climate challenges. The hope is that policy makers and regulators ensure that the roofs that are installed are of the quality needed to meet the capital's diverse and evolving agendas.

Basel In Basel, one of the most important pioneer projects at the time was the construction of an additional tract of the City's University Hospital, which foresaw green roof areas on all new buildings of the hospital complex. Patients should have a more pleasing view over the roof landscape, which in turn would ideally have beneficial effects on their healing process.

Research on sites like the University Hospital focused the potential for urban wildlife based on bird studies. The interesting results showing how black redstarts benefit from green roofs created a link to Dusty Gedge, an urban wild life specialist and planner in London. Dusty Gedge visited Basel in 2000 in regard of Stephan Brenneisen's bird and other studies. The knowledge of the benefits for black redstarts (a national endangered species in UK, with only two populations left in London and UK) by green roofs was the base for Dusty Gedge campaigning green roofs all over UK later.

Energy Saving Fund and the First Green Roof Campaign in Basel To get to the comprehensive green roof research of the University of Basel (later Zurich University of Applied Sciences, Wädenswil) the city of Basel did important contributions. In the early 1990s the city of Basel implemented an ecological mile stone with a new law to support energy saving measures. According to this unique law for Switzerland some 4% of all customers' energy bills are put into the "energy saving fund." Out of this fund campaigns and measures to support energy savings can be financed since then. As one of the benefits of green roofs is improving insulation and reducing energy consumption of buildings, a campaign for green roofs could be launched in 1996 based on the energy saving fund.

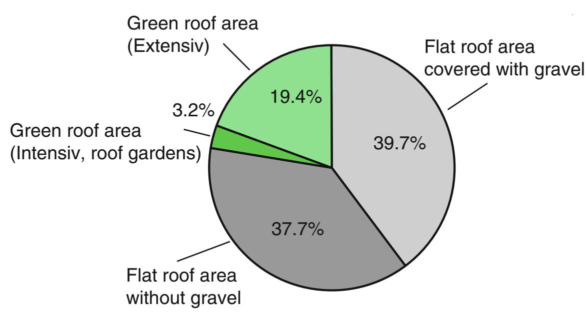
Following the "Year of Nature" in 1995 the project called "the improved roof" combined energy saving issues with nature conservation and got a total sum of one million Swiss Francs to subsidize house owners building their own green roofs. Within 18 months, over 120 green roofs were built in Basel, an area equal to 8 football fields. The project was carried out in cooperation with the trade association, which enhanced local know-how in the field. During the campaign, architects, planners, and the contractors installing the green roofs could get good practice and experience in this new technology – an important step to bring the measure into practice later.



Green Roof Planning in Urban Areas. Figure 2
Increase of green roof area in Basel, Switzerland, from 1970 until 2007

Building Code and Wildlife Potential After the first green roofs campaign, Basel Canton passed an amendment to its building code (paragraph 72) in 2002, requiring all new buildings with flat roofs to have green roofs. This amendment was made based on the various benefits and impacts green roofs have for the urban environment and not least in recognition of the potential for green roofs to support biodiversity and species conservation in Basel. It is supported by additional specific guidelines on implementing green roofs in Basel to maximize their nature conservation potential.

The recognition that green roofs provide valuable habitats and support nature conservation objectives was later one of the drivers for Basel's second campaign, which started in 2005. This second campaign funds both green roofs and roof insulation. It was funded in the same way as the first campaign with a total sum of SFr. 1.5Mio.



Green Roof Planning in Urban Areas. Figure 3
Percentage of green roof area related to the total flat roof area in Basel, Switzerland

Quantifying Green Roofs: Urban Heat Island, Climate Change, and Global Warming After the second campaign, again a survey recorded by aerial view photos the actual number and area of green roofs in the city of Basel. As a result 1,711 extensive green roof projects and 218 intensive green roofs (roof gardens) could be registered. So, approximately 23% of Basel's flat roof area is installed with green roofs in 2006 (Figs. 2 and 3). This amount will clearly have an increasing beneficial impact on the city climate. Regarding urban heat island problems accentuated by global warming the green roof policy of Basel could be an example: how to face one of the possible measures

Green Roof Planning in Urban Areas. Figure 4

with a campaigning strategy getting green roofs from pilot to mainstream successful.

Building Code and Price as Important Drivers for Success The general public in Basel still finds green roofs "special and exciting," but for developers, installing green roofs is now considered routine. The ongoing reduction of the installation prices of green roofs from SFr. 100.-/m^2 (US$90.-) in the 1990s down to SFr. 20.- (US$17.-) was an important factor in the inclusion of green roofs into the building code (Fig. 4).

Green Roofs in the Rest of the World: A Summary

Green roofs as an urban planning tool is not becoming more prevalent throughout the world. Although the approach evolved in Germany, Austria, and Switzerland, it is now spreading throughout Europe and North America, and there is increasing interest in South America, Asia, and Australasia.

The oldest green roof policies were derived in Germany and Austria in the early 1980s. Stuttgart in Germany is probably the most renowned of the Germany green roof cities, although green roofs are an integral part of planning in the cities of Munster, Frieburg, Berlin, Dusseldorf, and Munich, to name a few.

In 1985, the municipality of Linz in Austria undertook an assessment of the loss of green areas and the quality of life in the built environment through a unique mapping process, known as the Green Space Plan. Although there were a number of green roofs within the city's boundary, including one of the largest in Austria – the Schachemeyer Factory green roof, this research demonstrated the need for a more direct approach to encourage more uptake of green roofs. The research became the basis for legally binding building plans, which included an obligation for building green roofs.

Green roofs were seen as effective solutions to "greening" in areas of Linz where land use was not compatible with open space development. This was particularly important in the city's commercial and industrial zones. As a result, green roof policies were introduced in Linz in 1985 as legally binding and compulsory building plans. The direct impact of this strict measure led to an increase in green roofs, especially in the industrial areas close to the River Danube.

In 1989, the city of Linz instigated a generous financial incentive for building owners, by sponsoring green roofs by up to 30% of their, which was reduced in 2005 to 5%. Over the past 20 years, all these measures have resulted in over 404 green roofs being installed in what is by all accounts a relatively small city. The total area prior to 2007 was 400,000 m^2 (equivalent to 40 football-pitches). About 90% of this area is extensive green roofs and 10% intensive green roofs. However, the recent covering of the main motorway through the city with an intensive green roof (which talk all the city's annual green roof budget increased the total area by at least 40%.

In North America, many cities are now actively promoting the use of green roofs. The first city to undertake this process was the city of Portland followed by Chicago. Other cities include Seattle, Vancouver, Minneapolis, Toronto, Washington DC, and New York.

In Asia, the standard bearer for green roofs has been Singapore, which has been actively promoting green roofs for nearly 10 years and there is increasing interest from China and India in how green roofs can address urban health and environmental issues.

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Green Roofs, Ecological Functions

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Article Outline

Glossary

FLL The Landscape Research and Development Society (FLL) nonprofit organization was founded in 1975. Its mission is to research, produce, and disseminate all the various landscape development principles, guidelines, and specifications for the assurance of environmental quality [1].

FBB The Green Infrastructure Association (FBB) is a specialized group that was founded by some members of FLL to focus more specifically on green building. The FBB is the German counterpart to the American industry association Green roofs for Healthy Cities (GRHC) and one of the founding members of the World Green roof infrastructure Network (WGRIN). The German Word "Bauwerksbegrünung" has no translation in English – Green infrastructure in the sense of FBB is focused on all forms of urban green.

Extensive green roofs (EGR) also called natural green roofs, or eco-roofs, are vegetated roof constructions that require low maintenance. Drought-adapted plant species are used to create a self-sustaining vegetated surface suitable for nearly all types of buildings. Growing media is about 10-cm, or 3-in. thick [2]. The term "Natural Green Roof" is an own further term, which should set the main focus on enhancing the biodiversity on vegetated roofs. This can include in some regions irrigation with rain or gray water. Natural green roofs means engineered green roof systems under the guidance of nature conservations solutions. This term includes extensive and intensive green roofs.

Intensive green roofs (IGR) also known as roof gardens are garden structures on top of buildings and other artificial urban surfaces. In most cases, the growing media is more than 20 cm deep. For trees, it can be more than 1 m. IGRs, with structures including lawns, planter boxes, shrubs, and small trees, require the same maintenance as traditional gardens.

Storm water runoff Rain water running off impervious surfaces.

Green infrastructure overall phrase in the North America for all types of green roofs technology and other types of greenery on buildings, like vertical greening, living walls, and indoor greening systems. Green infrastructure in a wider sense includes photovoltaic technology and rainwater management.

Growing media engineered substrate for green roof purposes. Green roof substrates typically have low nutrient content and high drainage rates. Typical materials are expanded slate, shale, pumice, or recycled products.

Green infrastructure A term to describe the range of materials and technologies used to enhance urban environments. In addition to green roofs, this term also encompasses other related systems such as vegetated facades with climbers or living wall systems, indoor greening systems, rain gardens, photovoltaic systems, and other technologies. Roof greening can be combined with living walls, indoor plants, and ecological landscaping to enhance the built environment. The USEPA refers to structures specifically intended to manage wet weather as green infrastructure.

Leadership in Energy and Environmental Design (LEED) This is a US-based rating System by the US Green Building Council (USGBC). Benchmarks focus on energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship. The categories of achievement are: silver, gold, or platinum. In Australia, a similar rating system uses "stars." After an extensive debate about the merits of such certification systems, Germany set up one in 2009. Certification

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can be an effective type of marketing; however, one critique of existing systems is that there is not enough weight placed on vegetation.

Low impact development (LID) A storm water management and site-design technique to mimic the situation before construction of the settlements. Water usage, evaporation cooling, and water storage and drainage are such benefits of green roof infrastructures.

Definition

Green roofs are engineered constructions that include environments suitable for well-adapted plant species. In most cases, these types of roofing have a longer lifespan than conventional roofing surfaces. The following elements are built on top of the roof structure

– The underlying protective layer is made of an impervious material such as bitumen, rubber, polystyrene, or other similarly adequate technical materials, in short: roof protection membranes.
– Additional, root barrier layers are available to prevent the root penetration of lower layers. These are known as separation fabrics or geotextiles.
– This is commonly followed by a separate water-retaining layer, which could be a natural porous stone material or an artificial retention mat; in short, this is a drainage layer.
– On top of this layer, a filter fabric separates the retention layer from the next layer: the growing media.
– The growing media is, in most cases, a specially mixed lightweight soil material with well-selected components for storing rain water. Growing media are mixed for different purposes (for example, extensive green roof growing media differs from roof garden media in nutrient and humus content). Intensive roof garden growing media differs in that in the upper levels there is a higher content of humus and on the lower levels lower humus content.
– The vegetation layer can range from a shallow layer with mosses and only a few taller plants all the way up to full-blown roof gardens. As such, green roof maintenance requirements can be as little as an annual inspection or as much as is usual for ordinary gardens. The success of the vegetation layer depends on the careful selection of the other green roof layers. For example, if the goal is to plant trees on rooftops, a special combination of all these components is necessary.

The maximum weight of the construction must be calculated carefully. On average, it varies between 40 kg/m^2 (8.33 lb/ft^2) and can rise upward to about 350 kg/m^2 (71.7 lb/ft^2).

The longevity of green roofs depends on whether they can be easily accessed with the basic equipment needed for the success of the project as well as repairs. Maintenance and repairs must be planned carefully. Certain areas of the roof like, edges and places around roof fixtures like skylights or climate control systems can be prone to structural damage. Architects follows design visions, green roofs on "unusual" and for plant development difficult situations. Some times it is too high or to steep for a suitable plant growth or for the needed maintenance work. The technical and biological limits challenge green roof professionals. It is the duty of green roof specialists to figure out the limits, which are stet. Uncontrollable aspects of local climate, such as wind, temperature, and the intensity of storm events, can set limits to what is feasible from an architectural design perspective and ideas about developing living surfaces on roofs and facades.

Green roof technology has become internationally famous in the past few years. The books recommended at the end of this chapter offer a wide range of basic information from various regions in the world.

Introduction

The global human family is currently undergoing a subtle, revolutionary paradigm shift away from an unsustainable, industrialized, mass, homogenized, synchronized society to a sustainable, custom, micro, niche, bio-diverse world. This is seen in every aspect of human life – from the work to entertainment. Gone are the days when work was done 9–5, mass entertainment was enjoyed all together and gone is the factory fortnight in August where all headed for warmer climes for our 2 weeks of holiday. Today it's work and play around the clock telecommuting, working from home, downloading You Tube videos and interacting on Facebook and Skype. This global shift to an information-rich, knowledge society is mirrored in how the urban greening industry worldwide interprets itself.

Once upon a time, not long ago, a green roof predominantly meant an amenity space with garden furniture and well-manicured lawns and water features or maybe at its ecological best mass-produced Sedum mats laid over plastic drainage boards and geotextiles. With deeper movement into a sustainable concept of our lives, this has been replaced by ecological sensitivity, biodiversity concerns, water management and conservation, and other such similar ecological, sustainable ideas. This entry will discuss this shift in detail and what exactly it means.

Green Roofs as Ecosystems

In recent years, there has been a growth in interest in natural green roofs, or eco-roofs, as distinct from roof gardens due to the ecological benefits that may be derived. Roof gardens were traditionally installed in many countries to provide amenity space and for building beautification, in places such as hotels and resorts. The ecological benefits, such as thermal insulation, that were derived were almost an afterthought. Nowadays, in many instances, natural green roofs are installed to become natural ecosystems in urban areas. The benefits achieved by such installations can be measured not only in the building itself but the surrounding urban area as a whole.

Green roofs have been shown to mitigate the urban heat island effect. Two key studies in the hot summer climate of Athens [1–3] concluded that the thermodynamics of both the building and the surrounding area are effected by the natural green roof installation studied on the Greek Treasury in Constitution Square in Athens. In addition, leading natural green roof researchers have compiled a review article, which explains this technology [4]. The concept of natural ecosystem green roofs may have grown out of the idea of just letting pioneer plant species grow on built surfaces in urban areas. Certainly, where this idea originated is a moot point now as it has become an emerging architectural style, which is being used by leading name architects with global reputations.

Natural green roofs are also called bio-mimicry or bio-phillic architecture [5, 6]. Ecologically, natural green roofs can be compared to natural structures such as rocky outcrops or cliffs where harsh weather conditions and shallow layers of substrate are found. It is understandable why cities are sometimes described as being "urban canyons." Many highly specialized ecosystems thrive in such structures [7]. In fact, these ecosystems, in the natural world, have often developed because of these extreme environments.

A number of environmental scientists and thermodynamics researchers are working on quantifying the energy savings, emissions reductions, and water resource management benefits that come from the use of natural green roofs. In addition, research is being conducted to quantify the many other ecological other benefits such as the reestablishment of plant and animal biodiversity in urban areas. Green roofs can be considered as the open ecosystems described by early ecologists [8]; where inputs of water, nutrients, and substrate to such installations occur from precipitation, dust in the urban canyon, and gaseous pollution. Losses to a natural green roof can come from wind erosion and storm water runoff. In terms of ecological productivity, natural green roofs have been compared to desert ecosystems, where there is a similar input/loss situation.

The total phyto-mass of a natural green roof is measured by considering the total shoot/root biomass. This figure varies in Europe between 100 and 500 g/m^2 total dry organic matter [9]. The 500 g/m^2 is an almost fully covered natural green roof, which has been planted with Sedum or similar succulents, Chive (Allium spec.), wildflowers, pioneers, and grasses with about a 95% coverage and about a height of 25 cm. The figure for a south-facing roof with coverage up to 60% is about 100 g biomass/m^2. The gaseous exchange (O_2, CO_2) productivity of such ecosystems is relatively low when compared with richer ecosystems such as forests. A biomass survey found a natural green roof with a 168 g/m^2 above ground biomass and about 107 g/m^2 root system biomass 2 years after installation [10]. These recent dry matter values are similar to the above-mentioned German measurement from the 1980s. If the main aim of the installation of a natural green roof is CO_2 sequestration, annual cutting of the plants is recommended for mulching, followed by allowing the plants to grow back each year. Natural green roofs are also being seriously considered to not only supplement urban agriculture to supply cities, particularly in the third world, but also in the West, as urban agriculture can lead to significant emissions reductions. This is due to the fact that food can be sourced and consumed locally, reducing the need for transportation from rural areas into cities. There are notable examples of this emerging concept abound, across the world, from New York City to Bangladesh. Urban agriculture is substantially more productive using high-tech hydroponics and other such intensive technologies than it is with natural green roofs. So, green roofs can be used to supplement urban agriculture. In addition, natural green roofs can provide specialist agricultural products such as aromatic herbs for culinary and pharmaceutical use.

Natural green roofs are usually designed to keep vegetation conditions stable over the long term. However, there is a growing belief, particularly among natural green roof pioneers in Greece, that natural biological succession could result in the development of highly successful, bio-diverse, specialist ecosystems, which have adapted to the peculiarities of urban centers. On the whole, human intervention and "maintenance" should be kept to a bare minimum, if not removed altogether. It should be noted that it is advisable that a specialist inspect a natural green roof annually to check the waterproofing and to make sure that the vegetation has not become dangerous in terms of height. Apart from that, nature should be allowed a free reign. It must be noted that natural green roofs are not usually designed as recreational space. Furthermore, safety concerns relating to the height of the vegetation must be addressed. Barriers to prevent falling of material must be installed around natural green roofs.

Natural green roofs, then, can be considered extreme man-started natural habitats on artificial urban surfaces. After the installation annual inspection means that these structures require low to nonexistent human intervention. Environmentalists are becoming increasingly interested in the almost self-sustaining nature of natural green roofs. Overall, researchers are beginning to realize that they may well be able to reduce the anthropogenic impact of urban environments on the biosphere. The level of this impact depends on a plethora of factors, yet, these can be engineered by the design of the structure.

In this entry, three main aspects of natural green roofs will be highlighted. First of all, the benefits of natural green roofs will be discussed. To assess this, a description of natural green roofs as ecosystems will now be made.

Green roofing is currently (2010) practiced in about 40 countries worldwide please see www.worldgreenroof.org. There are organized green roof associations in about 20 countries at the time of writing [11]. Also, about 500 peer-reviewed articles have been published concerning green roofs at the time of writing this article. This would suggest that while green roof technology appears to be quite simple and low tech. the concept, particularly natural green roofs, is in fact complex [12]. Much more research is required and will be conducted going forward.

What is required is a comprehensive picture, based on research, of what exactly are the benefits of natural green roofs. It is certain that all forms of green roofs and green walls will play a fundamental role in terms of thermal insulation for buildings and for mitigation of the urban heat island effect in the future.

It seems certain that the performances of natural green roofs will aid a revised perception of what is aesthetically pleasing toward natural green roofs and away from traditional roof gardens. The new perception will be that bio-phillic is better than manicured human-created gardens [13]. The description of the ecological functions of natural green roofs by pioneers, such as James Todd [14] and his more modern counterparts such as Peck [15] and green roof enthusiasts, campaigners, and activists like Dusty Gedge in the UK (www.livingroos.org), helps to create new paradigm in what a green roof should look like. When the thermal insulation performances of natural green roofs are combined with water conservation and enhanced biodiversity on a massive scale around the world, a technology emerges, which could ameliorate, if not solve, some of the most pressing concerns of our time. This technology may soon become the status quo in architecture.

One of the main challenges of the urban greening industry and its stakeholders now and in the future is to obtain a full and detailed understanding of a natural green roof ecosystem, its energy cycle, and how these systems interact with other green technologies. It must be stated that there are already peer-reviewed articles, which begin to provide insight into this complexity and could make substantial contributions to architectural textbooks in the coming years.

It should be pointed out that roof gardens or intensive green roofs, which are primarily constructed as amenity and recreational space in towns, could also be used for ecological concerns. For example, if roof garden decks are built with rainwater catchments and rainwater storage systems, there are ecological benefits that can be achieved. The deeper substrates that are used in roof gardens, which often range between 50 cm and 2 m offer enough substrate depth for many species of shrubs and small trees. Of course, safety issues must always be addressed before planting taller plants because at roof level, falling plant is a serious concern. When done properly, urban forestry may be possible on roof top spaces. Susan Weiler's Church project [16] is one example of an attempt to achieve urban forestry. While this project is about traditional horticultural ideas of aesthetics, it does also incorporate the use of trees using forest mimicry. It must be noted, once more, that safety must always be put first when dealing with the urban environment. Which tree species have been considered as suitable for urban forestry? First of all, many common or ornamental plant species have been considered. All phyto-mass-related functions can be delivered. Research about the potential of such forestry structures on rooftops has been conducted and tested in Hong Kong [17].

One conclusion of this entry is that if the load capacity of a building allows greater structural weight, a deeper growing medium opens up a wider range of potential plants species for selection as long as the aforementioned issue of falling has been addressed thoroughly. Consequently, urban forestry becomes possible along with natural green roofs. The challenge for the urban planner is to find appropriate mixes of planting schemes and appropriate safe technologies for particular climatic conditions and building codes. In recent years, forestry structures that have been installed on buildings range from sparse plantings to full earth shelters with copse planting schemes. Greened buildings, then, can have significant thermal performances and also act as natural corridors for the reintroduction of nature into urban areas [18].

Introduction to the Three Main Benefits

Green roofs, and especially roof gardens, offer aesthetic benefits and urban amenity and recreational space for city inhabitants. The measurable ecological and economic benefits that are derived by urban greening make these technologies increasingly attractive to town planners, architects, and civil engineers alike [19]. Roof greening serves both private and public interests. There are also local and global benefits.

Proponents of green roof technologies, such as The World Green Roof Infrastructure Network, (http://worldgreenroof.org) believe that all local and national governments should institute incentives to encourage the implementation of massive scale urban greening. The experience of German roof greening, in the last 30 years, suggests that government incentives to individuals, businesses, and the state lead to significant increases in the implementation of these technologies. This model can be copied around the world. To date, the cities that have taken these technologies most seriously resulting in large-scale implementation are mainly found in Germany. Cities such as Berlin and Stuttgart have high adoption rates, which are measured in percentage points of available city area. It must be noted that cities such as the Austrian city of Linz follow close behind. A full overview of the state of roof greening in Europe was given in a workshop at the World Green roof congress in Nürtingen 2009 [20, 21].

Some European Cites, such as Copenhagen, Malmö, and London, are jumping on the roof greening bandwagon with ambitious plans for roof greening in the coming years. An important next step in the implementation of large-scale greening globally is the mapping and modeling of successful initiatives that are being taken by local and national governments, agencies, and stakeholders.

The three main benefits that are derived by roof greening are the following:

1. The influence on the urban water management cycle
2. The energetic performance of green roofs related to the buildings, the city, and the planet as a whole
3. The development of urban biodiversity, leading to a richness of flora and fauna in urban areas

The Urban Water Management Budget The urban water management budget is stressed by the impervious surfaces of a built environment. In the natural world, storm water runoff forms a small percentage of the total water volume that falls as precipitation. Most of the water that falls as precipitation, in the natural world, is absorbed by the Earth and becomes ground water. The reverse is true in the urban built environment: Most of the water that falls as precipitation becomes runoff. This causes a number of problems. Athens may be representative of what happens during a storm. The city squares are turned into lakes, and the streets become rivers within minutes of the onset of a storm event. Recent research into urban water management budgets conducted by Göbel et al. [22] suggests that urban landscapes could be transformed using a combination of rainwater catchment and retention areas, use and absorption, which would reduce urban water management costs to a level not much different from water management costs found in the natural world. In this context, green roofs are important as a type of decentralized rain water catchment and retention system. Green roofs and vegetated facades can retain storm water and release excesses over a period of hours, if not days. Green roofs act as a brake on runoff as they absorb and store large percentage of the water that falls as precipitation in a similar method to that which is found in the natural world.

Rainwater management with green roofs can incorporate storage values not only in the growing media but in all other layers in green roof systems. The drainage layer can be used for storage. Surface and subterraneous ponding can be designed to allow further storage. In addition to the defined water capacity of the growing media, drainage/storage layer, ponding, in countries where monsoon and excessively heavy rainfall events are experienced, growing media can be designed and plants selected that can store even larger quantities of water. Again safety issues are an important consideration here because water is heavy, so permissible static loads must be taken into account, particularly in seismic regions of the world. Consequently, it becomes clear how runoff is reduced in quantity and delayed over time by green roofs.

When green roofs are combined with other rainwater catchment and retention technologies, such as rainwater harvesting, re-use, and infiltration, it is possible to create a zero runoff position in a city. The decentralized storm water retention property of green roofs also reduces pressures on wastewater treatment systems that are already overloaded. The peak runoff after a heavy storm event is minimized.

This ability of green roofs to catch and store rainwater also has an impact on the second major benefit of green roofs in their thermodynamic properties. Surface runoff rates and the lack of green spaces can explain why there is almost no evaporation and why urban climates can be hot and dry [23]. With the increasing number of megacities, this climate may contribute to health problems for many citizens [24]. As will be seen in the next section, green roofs are active thermodynamically. This sets them well apart in terms of their thermal performance from conventional forms of thermal insulation using materials like stone wool and polystyrene. This will be discussed further shortly. For now, it can simply be stated that the captured water in a green roof, during a storm event, is evapotranspired by the plants. This actively cools hot cities. This cooling effect reduces air conditioning demands. Reduced air conditioning use further cools the city, leading to a virtuous cycle. This will be discussed later.

In developed countries, in the next few years, sewer systems that are approaching the 100 years of age mark will need to be replaced. The decentralized water management nature of green roofs, which reduces storm water runoff quantities in cities can provide a viable solution to this issue. This has been demonstrated in Berlin [25]. Since the 1980s, numerous projects to reduce storm water runoff, manage water demands, and handle wastewater disposal in cities have been implemented in Berlin; 17 projects were documented, and a list of these projects is downloadable from the official webpage of the Berlin senate [26]. Green roofs and green walls are fundamental components of green building technologies in all of these projects [27].

Increasingly, over the years, peak runoff during heavy storm events as well as the "Urban heat island effect" has become ongoing and challenging problems in inner City water management. Open evaporative surfaces could well become mandatory solutions [28]. In Berlin-Brandenburg, about 80% of the total precipitation that falls is converted to evaporation using various technologies and methods, which include green roofs. This figure could become an achievable target for all cities on Earth. This also links to the third benefit of green roofs, which is the development of natural ecosystems in urban areas.

In Berlin, for example, for each type of inner city habitat, an optimized vegetation value can be calculated. In Berlin, this value is referred to as the "biotope area factor." These basic strategies must be adapted to suit regional climates with appropriate plants and growing media alternatives and local building codes. A further link between the benefits of green roofs is their effect on the so-called urban heat island effect, which links the water retention benefit with the thermodynamic performance. The urban heat island effect is partly caused by the almost nonexistent property of evapotranspiration in a city. By retaining more water in urban structures in green roofs, the city is cooled in the summer, mitigating this phenomenon. In addition, in an emerging paradigm among climate specialists, water cycles are now considered to have a fundamental causal relationship with man-caused global warming [29].

To develop large-scale vegetation structures on buildings, cooperation between architectural disciplines and green planners, researchers and designers must begin; the conventional so-called black roofers, who use bituminous and plastic membranes, and so-called green roofers, who use water storage/drainage systems, substrates, and plants, must engage in productive dialogue.

Currently, about 5–10% of new buildings in Germany have green roofs. The number of green walls remains, at present, less than 1%. This potentially represents a huge opportunity for environmentally friendly architecture. A paradigm change in architecture is needed to construct not only in terms of energy-efficient designs but also buildings that have zero negative impacts on the environment. This is the challenge for the coming years, and green infrastructure will play a dominant role in assisting cites to achieve this objective [30].

Energy At the dawn of the twenty-first century, humanity faces what could possibly become its defining moment. The choice is becoming ever more obvious, and humanity is going to be forced to make a decision soon, en masse, about whether humanity makes it to the twenty-second century or becomes just another flash in the pan for this planet. The human race potentially faces the horrific possibility of a massive die-off at the very least or extinction at its worst. The reason is quite simple: Mankind has been able to develop modern civilization on the Earth, and achieve the undreamed of standards of living and technologies that it has due to the tremendous subsidy that abundant oil has provided. One liter of oil is the energy equivalent to 100 man-hours of labor. The West has collectively burned or used a large percentage of the oil reserves on Earth during the last 100 years. How much oil has been used and how much is left is open to debate and probably unknowable. More may be found somewhere, sometime. What cannot be debated is the fact that oil is a finite resource, which took millions of years to form, and if only the West continued using it at the rate that it does, it will dry up sooner or later. This is likely to be sooner rather than later because now the rest of the world is developing at rates that make Western industrial development in the late eighteenth and early nineteenth century looks like child's play [31].

In addition, climate change, global warming, the coming ice age, how much influence human activities have on the Earth may be debated endlessly. What cannot be questioned is that continued production of CO_2, CO, and a multitude of other poisonous gases through oil combustion, ongoing quarrying, mining, deforestation, increased urban development, natural ecosystem degradation cannot end well for humanity or for most forms of life. It is inevitable that, again, sooner or later, the human species will have cut down the last tree, used the last drop of water, polluted everything, everywhere, and this is obviously not beneficial for life.

Certain issues require detailed, analytical, scientific study and understanding to attain a deep awareness. This issue can be understood by common sense alone, most effectively. If you keep taking something from a finite source, sooner or later, there will be none left. Moreover, if by using the finite resource taken, degradation of your life-support systems occurs; the end to this scenario does not require much thought to calculate.

So, humanity faces three of what are possibly the greatest challenges any species can face. The first is increasing rates of depletion of ever dwindling energy and natural resource supplies, the second a buildup of toxic waste in its environment, the third exploding population growth. Thankfully, a viable solution to these three scary challenges is available. While it is true that these points may seem exaggerated and the solution simplified. Increasing numbers of highly acclaimed scientists from around the world are suggesting that the solution comes from the cause of the problem. Nature is the issue, and nature is the solution.

Some activists and campaigners state that there is a need to save the Earth. The Earth has been here, according to most estimates, for 4.5 billion years. In that time, it has survived far greater threats than humanity. Possibly, what humanity needs to do is to save itself. The only savior up to the task is nature itself. This is where urban greening and particularly green roofs really prove their value. Green roofing may well be the ultimate "return to nature" that was much touted by groups in the 1960s and subsequent eco-friendly parties and interests but this is a "return to nature" without having to move anywhere. Cities, can be taken, as there are and transformed into natural ecosystems using green roofs. The impact of this on the challenges would be, to understate it, revolutionary and evolutionary.

Possibly, the most serious and important impact of this would be its effect on human energy requirements. Numerous studies conducted around the world have shown that green roofs significantly reduce heating and particularly cooling requirements in both buildings and whole cities. In the aforementioned thermodynamic study of the oikostegi (natural green roof in Greek) installed at The Greek Treasury in Constitution Square, opposite the Greek Parliament in Athens, Drs. Rogdakis Ph.D., and Koronaki Ph.D., concluded that substantial thermodynamic effects were observed.

Air conditioning requirements were reduced by 50% in the floor directly beneath the green roof installation. This is important when one considers that only 52% of the roof surface is covered by the oikostegi natural green roof. A further important conclusion of the study was the so-called thermal lag effect of the green roof. Peak environmental temperatures were observed at 1 p.m., the building temperature peaked 30 min later where it was not greened, and the area that was greened peaked a full 90 min later at 3 p.m. This is rather important for two reasons. Firstly, due to the fact that only 52% is greened, there are large thermal bridges, which would not be observed had the entire surface been greened. Secondly, this particular building houses government offices and the peak demand for cooling of the building has been delayed by the natural green roof until 3 p.m., at which time the civil servants have already gone home. This means that there are further reductions in air conditioning because it is no longer required. Before the installation, peak requirements were observed 90 min earlier. On the surface, this may not appear substantial but the Treasury has an air conditioned office space that totals nearly 12,500 m^2 http://www.oikosteges.gr/index.php/greenroofs/research.

Another important aspect of the thermodynamics of green roofs is the fact that because air conditioning use is reduced, further reductions in the ambient temperature of the surrounding area are reduced leading to even further reductions in cooling requirements. It was anecdotally stated by a Greek thermodynamics specialist that if all the air conditioning were switched off in Athens for 3 days, Athens would not need air conditioning. The reason for this is simple. The inventor of air conditioning, Carrier, never designed it as a method of cooling. It was designed to condition the air. The way air conditioning works is by taking hot air out of a building and dumping it into the surrounding area. This means that the surrounding area becomes hotter leading to an increased requirement for air conditioning leading to increased dumping, leading to a vicious circle. What green roofs do is to reduce air conditioning requirement, leading to falling ambient temperatures in the city, leading to further reductions in air conditioning requirements in a virtuous circle. Large-scale implementation of green roofs leads to a lowering of peak summer temperatures in cities, which leads to a lowered energy requirement to run air conditioning units and lowered peak ambient temperatures.

A similar story is observed in the winter with heating requirement reductions. This number of reduction depends on various factors, but the values vary between a few percentage up to 20% in roof top level apartments [43]. Reducing energy requirements with green roofs has another important impact, especially in countries like Greece and Germany where lignite is burned to produce electricity by the Public Power Corporations in both countries. Lignite burning produces even greater carbon emissions than oil burning and is much less efficient. Carbon is one of the main greenhouse gases, which are thought to be partially responsible for global warming. Energy efficiencies achieved by green roofs, then directly reduce carbon emissions, reducing greenhouse gases and slowing down global warming. It must be noted here that green roofs also absorb greenhouse gases, further reducing existing emissions. The full impact of green roofs is still not completely known, and there is room for much research. Having said that there is little doubt that they have a substantially important impact on reducing energy requirements, which has an impact on reducing emissions and heat caused by air conditioning, which has a further impact on reducing energy requirements in a virtuous circle.

In Europe, the goal for fossil fuel consumption reductions stands at 40% by the year 2020. Furthermore, European countries have pledged to reduce carbon emissions by between 10% and 20% by 2020. Greece has ambitious plans to reduce carbon emissions by 30% by 2020. All of these goals become achievable using massive scale urban greening using green roofs. Green roofs can return their installment investment cost many times over in energy requirement reductions and emission reductions very quickly.

It should be stated here that green roofs operate rather differently from other forms of thermal insulation. A green roof is an active cooling and heating device as well as a superior form of thermal insulation. Conventional insulation isolates the environment from the building, keeping heat out of the building in the summer or by trapping heat inside the building in the winter. The way it works is by creating a thermal barrier between the building and the outside environment, which prevents thermal flow. A number of materials are used, including stone wool and polystyrene.

A green roof insulates a building in this way, but it also plays a more active role in the thermodynamics of the building and, in fact, the surrounding environment. First of all, it acts as a thermal pump in the summer. Heat that is in the building is drawn out by the green roof as the green roof temperature is lower than the environment and the building. Also, a green roof lowers ambient temperatures in the surrounding area. So, if green roofs are installed on a large scale, ambient temperatures would fall in the whole city in the summer. The same is not true for conventional thermal insulation. Moreover, as stated earlier, as ambient temperatures fall, air conditioning use falls leading to further falling ambient temperatures. Again, this only applies to green roofs.

Evaporative cooling consumption by green roofs is the name given to these processes. Further improvements to the performance of green roofs can be made if rainwater catchments and green roof irrigation are utilized. This is known as adiabatic cooling, which is a low energetic cooling process in which rainwater can be used.

If roof surfaces are extensively greened, storm water runoff can be detained and retained [28] to irrigate the green roof during the summer to improve the thermal performance still further using evapotranspiration.

So, the evaporation of water in a city is an important component to reduce the heat impact of solar radiation in a city. Lower evaporation rates mean higher surface temperatures and in urban areas a main contributor to the "urban heat island effect." On a global scale, the reduction in evaporation in the built environment is mainly responsible for climate change [29]. Mitigation of global warming by evaporative cooling is one key process, which can be used in the reduction of global warming. A special entry on this was delivered at the climate conference to Copenhagen by Kravčík et al. The conclusion of the entry is that global warming is related to the loss of vegetation worldwide. Green roofs offer new space for vegetation structures and provide the needed evaporation cooling systems.

Biodiversity Urban biodiversity is the third benefit that green roofs provide. The Convention on Biodiversity (compare: http://www.cbd.int/cop9) COP9 Declaration of the Congress in Erfurt in May 2008 demanded that green roof plant selection foster and encourage urban biodiversity. Environmental laws, such as environmental building codes, help to mandate these demands at the national level. Planting trees wherever possible in a city is the first step in solving the issue. This is possible on parking space areas in the commuter zones of cities; tree planting in cities also reduces the air conditioning requirements in cars that have been in the shade, when driving recommences. Parking decks can utilize shade trees to protect cars from direct solar heating. This reduces air conditioning requirements in cars, which again feds into the virtuous circle mentioned earlier. Parking decks are an important source for greenery. In Singapore, for example, there is a government program to set up green roofs in parking areas as an open space resource.

Most natural green roofs (NGRs) are promoted as self-sustaining ecosystems. A plant cover of about 60–75% indicates that a high-quality green roof has been achieved; however, in many cases, the focus is only on few specific types of plant species. NGRs can and should also be designed to encompass a high range of biodiversity. Depending on the type of the project, a focus on regional native plants can be integrated into the design of the installation. To achieve this end, the right selection of plant species, proper design of substrates, and a variety of different methods of ecosystem establishment are important.

The number of plant species on a green roof depends on a number of parameters, such as the manner in which plants are introduced to green roofs. The following is a brief description of the most common methods of plant establishment:

– Seeding (affordable for flat roofs).
– Sedum sprigs (cheap and easy, establishment takes about 1 year).
– Plugs – there are a nurseries, in countries where roof greening is popular, around the world, that specialize in green roof plants.
– Preproduced turf mats. This technology was developed a few decades ago. Most of the turf mats include drought-adapted grasses and also several *Sedum* species. Depending on the local situation, grasses are often the best competitors under shady conditions, and *Sedum* species are usually the winners in the areas with full sun. This method offers a complete vegetation cover from the first day of installation. This is important for pitched green roofs and high-rise buildings with a high wind uplift to avoid the erosion of soil and decline of plant species.

Seasonal changes in the vegetation structure can be observed. The timing of blooming on extensive green roofs is related to the frequency of rain events. In humid and wet summer seasons, more flowering is normal; also more pioneer plants invade spontaneously during wet seasons. The acceptance of unplanned plant species depends on the aims of the project.

Weed Control Some plants are known to be difficult plant species for NGRs. These must be removed as early as possible. An annual inspection and weeding can be helpful. Also, it must added that this is an issue of great debate in the green roof world. Weeds can be defined as plants that grow and are not wanted. Some so-called weeds can be invasive and dominate if they are not controlled, which may or may not be desirable. Another way of looking at a weed is in terms of biological succession. Weeds are really pioneers. They are plants that take over barren desert like environments to begin to nature's slow process back to a climatic ecosystem. Nature is innately wise and so if the building owner, the architect, and the green roofer are aware, then weeds can be viewed as pioneers and a desirable addition to a natural green roof.

Water Management by Green Roofs, an Overview

Approach The most desirable situation in terms of water management, in a city, is to achieve zero runoff and 100% evapotranspiration of precipitation. Green roofs detain and store water by absorbing it in the ways mentioned earlier. This stored watered is then evapotranspired by the plants. The rate of evapotranspiration on a green roof is dependent on the amount of water captured by the NGR.

In order to calculate the various components of the NGR water budget, meteorological data are needed. It is easy to measure precipitation (normally with tipping buckets). Runoff can also be measured quite easily by installing adapted tipping buckets in the downspout. The water content stored in NGR substrates can be measured either with a type of roof lysimeter, or it must be calculated via a typical water budget equation, like HAUDE or others (Figs. 6 and 7).

Currently, about ten research institutions are working on this question to get realistic numbers on the retention rates by measurements on natural green roofs. Such experiments are being conducted globally and on different scales. Scale ranges from the module scale of a small research field, to measurements on small newly constructed test houses of a few square meter, like in PennState State researches in the US or measurements on realistic research roofs, to even larger study areas, like in Neubrandenburg or Berlin [31]. Since 2003, a green roof research facility has been collecting similar data in the British Columbia Institute of Technology (BCIT) in Vancouver [32].

This data about how green roofs perform is a major contribution to "applied ecological research." Other working groups are using this data to simulate the effects of NGRs at city blocks, neighborhood, and on even larger scales.

To test the performance of green roofs materials, like the drainage layer and growing media, the FLL [34] developed physical test procedures. These tests were carried out in replicate; however, they were only performed on the growing media without a vegetation layer. Research facilities on a real roof situation perform more realistically than test plots at research facilities. Green roof plant species need realistic harsh weather conditions of wind and drying out of growing media [33]. Thus, these values are comparable to but lower than real measurements done on real roofs.

The retention values are counted in different ways [33]. Compared annual retention rates of 12 different research institutions from Germany, Sweden, Belgium, and USA were made. The annual retention rates ranged between 42% and up to 80% on flat NGRs. For sewage calculation, the peak load capacity is the most important value. To count this, a technical report is included in the FLL guideline on how to make replicable measurements [34]. In Germany, all growing media must be certified with this value.

The effect of a pitched roof has no significant influence on the percolation of water, this was another early finding on German test plots situated in Hannover [35].

An Italian group [33] carried this idea further and investigated it in Mediterranean climate over a duration of 18 months' rain events with varying intensities. If the total rain event was less than 10 mm, during periods of good ground coverage (75% +) by the NGR, nearly 100% was retained. During the heaviest rain event of 132 mm in November, only 10% of the precipitation was retained; however, the peak flow reduction was nearly 80%. The time lag from the beginning of the rain of this major rain event and discharge was 148 min compared to almost immediate discharge on an exposed roof. This braking effect of an NGR is most significant for flood control in a city.

An interesting observation is the differing data requirements between professions, such as ecologists and civil engineers, who are responsible for drainage systems of cities.

The debate about NGRs rainwater retention benefits has two aspects:

– How can water be captured by the vegetation structures as well as in a storage tank? Is irrigation also a suitable solution for NGRs? After all, irrigation does help to reduce high temperatures, particularly in the late afternoon hours in summer. How can the evaporative cooling effect be measured?
– The integration of green roofs into a rainwater management strategy to achieve "zero runoff" from a property is desirable. This would also help to reduce mixed sewage overloads of inner city sewer systems. A combination of green roofs, artificial ponds, rainwater harvesting, and infiltration could indeed result in a "zero runoff strategy." Local solutions are needed to achieve this goal for each property and for individual regions. Green roof technology is a "decentralized" technology. Political instruments, like the "runoff tax," in Germany, could be helpful in establishing these strategies in city policies [36, 37].

Evaporation takes place for several days after a rain event on a NGR. The actual evapotranspiration amount depends on the amount of stored water in the substrate, the temperature, the air humidity, solar radiation, and wind speed. The amount of real evapotranspiration water on a NGR in central Europe varies in summer between 0 mm/day (dried out growing media) and 4.5 mm/day in saturated conditions in Neubrandenburg. In most cases, on extensive green roofs in Germany, there are drought conditions [38].

The measured evapotranspiration, by a agricultural field lysimeter station in Berlin, can be up to 8 mm/day. The potential evaporation on green roofs is high due to high solar radiation rates on a roof, high wind speeds, high temperatures, and low humidity in cities.

The full year measurements allow for selection periods with interesting parameters, the following case studies show the range of experiments that have been conducted:

(a) Summer, dry or wet growing media – a light rain event
(b) Summer, dry soil, heavy rain event
(c) Summer, long wet period, effect of rain events
(d) Winter, wet growing media, no frost some rain
(e) Winter, wet growing media, frost, snow layer
(f) Winter, wet growing media, frost, snow melt, more rain

When such periods are selected from the data set, what happens?

(a) In the summer situation, nearly all rain quantities can be retained and be evaporated over the following days.
(b) Surface runoff is lower if the vegetation cover is complete and the green roof is not inclined. On flat roofs, in normal situations, the rainwater will be retained in the coarse structure of the soil and by some ponding on the roof. In experiments, the quantity of the runoff was reduced and the time lag between the rain event and discharge was increased, as already mentioned, when a green roof was installed [39].
(c) The diploma work of Bustorf [40] recorded during a 10-mm precipitation event in the summer in a wet period. A 50% storage capacity in the growing media, with the additional 50%, i.e., 5 mm, being detained for a number of hours and discharged slowly.

Various research groups from Neubrandenburg, Berlin but also in other climate regions have found remarkably similar results.

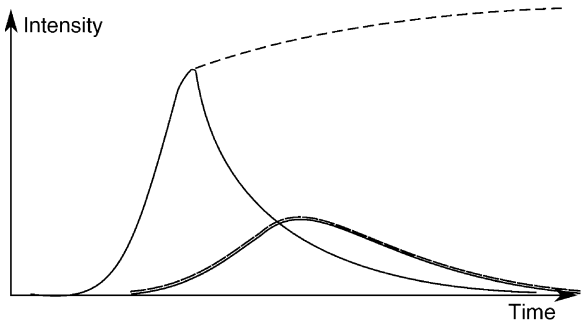
Figure 1 shows the typical structure of a rain event. Peak intensity is achieved rapidly followed by a much longer duration with lower intensity.

Green roofs arrest discharge for an extended duration, which, in most cases, is as long as 15–20 min after the onset of the rain event. On an exposed roof without a green roof, discharge is instant and complete. If some extra retention technology is incorporated into the green roof system, this time lag can be extended indefinitely. In terms of urban water management, time lag is critical. All impervious services, as is known, and as has been stated, have instant and complete runoff. That is why city streets become flooded during a storm event.

In addition, as already stated, discharge is also arrested and runoff is always much less on a green roof, making it easy for aging urban drainage channels to accommodate the minor amounts of runoff.

Table 1 shows evaporation capacity of NGRs without irrigation in the Northeastern German climate. The results of lysimeter measurements demonstrate that evaporation also occurs in winter. Summer evaporation rates depend on the amount of water stored in the growing media. Three millimeters per day of evaporation is the mean under saturated conditions (Fig. 2).

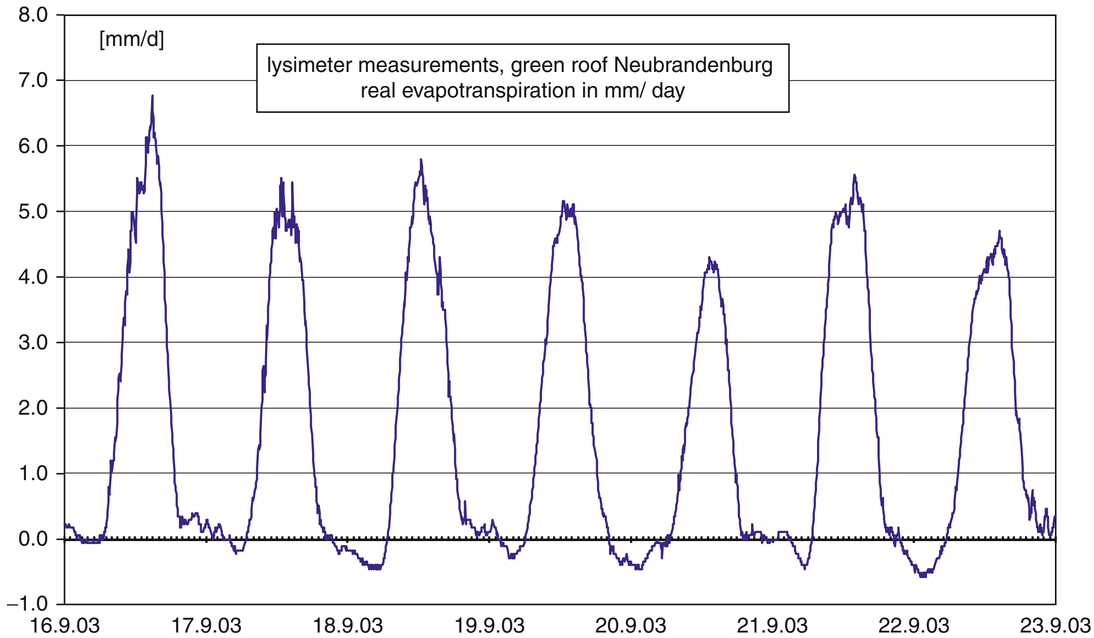
The Table 2: shows the real evapotranspiration of a green roof lysimeter in mm/day. At night, the condensation process can also be observed. The



Green Roofs, Ecological Functions. Figure 1
Schematic function of green roof retention values. Typically, peak rain full quantity is achieved shortly after the onset of the rain event followed by decreased rainfall quantities over time as the event develops. In layman's terms, a short downpour is usually followed by subsequent ongoing drizzle in many if not most storm events. Consequently, green roofs are able to absorb the initial peak and then break the subsequent runoff occurring from the ongoing drizzle. In conclusion, the function of a green roof is to absorb initial storm event precipitation, store the water, and break the runoff of subsequent rainfall. The stored water is then evapotranspired over a matter of days and maybe even weeks after the rain event

Green Roofs, Ecological Functions. Table 1 Daily evaporation rates during different seasons (own lysimeter measurements, Neubrandenburg) [41 Koehler 2004, updated)]

Season	Evaporation values in (mm/day)	Growing media saturation
Winter	0.1–0.5	Well saturated, no frost
Spring/autumn	0.6–1.5	Well saturated
Summer, hot	1.5–4.5	Well saturated
Summer, hot	0.0–0.2	Dry substrate



Green Roofs, Ecological Functions. Figure 2
Real evapotranspiration of a green roof in Neubrandenburg under saturated conditions, measured by lysimeters (compare Fig. 7)

evaporation of 1 mm of water means 1 L/m^2 converts 680 Wh of energy into latent heat. The resultant cooling rate of 3 mm/m^2/of evapotranspiration in summer represents 2,040 Wh.

After more than 10 days without rain, green roofs, which have not been designed for extended drought show evidence of stressed conditions due to the lack of water in the system. Specially designed natural green roof systems, such as the Greek oikosteges natural green roof ecosystem, have been able to survive for over 6 months without any inputs of water. So, while the evaporative cooling capacity of a green roof may decrease the dry growing media, it still acts as a thermal insulation layer. This means that the green roof medium provides good insulation but is not always beneficial to the plants unless the whole system is purposely designed for such situations. It is the designer's responsibility to manage this conflict, by installing an irrigation system, accepting drought in the vegetation or designing systems for such situations. Under normal cases, most green roof plants regenerate again, when it rains.

In most models and simulations of the potential daily evaporation rates of NGRs, rates are usually taken from calculations from data provided by standard meteorology stations, which focus on agricultural crop production. The difference with extensive green roofs is the vegetation's ability to survive quite long periods of water stress and regenerate like desert plant species. *Poa compressa* is an example of a plant that has this ability. If the goal is to create a constant cooling system with green roofs, then irrigation is advisable.

Studies measure the long-term retention by an extensive green roof. In Hannover, the effect of distance from the nearest drain to the point of study on retention and discharge rates was studied. The experiment systems studied were designed according to FLL green roof design guidelines. This study showed that discharge rate and discharge volume were dependent on the depth of the growing media, total green roof area, the roof inclination, and the distance to the nearest drain. The discharge values differ between 0.6 for very shallow substrates of about 4 cm and 0.4 for 15–20 cm depths under controlled conditions in green houses. The substrates were filled into boxes, which were then fully saturated with water before being subjected to periods of experimental rainfall. This enabled different growing media to be compared. The influence of plant species was not tested by this model.

Green Roofs, Ecological Functions. Table 2 Energy demands of evaporation of rain water on different roof surfaces mean daily values [38, 41]

Roof surfaces	Net Radiation Wh/m²/day	Latent heat flux Wh/ m²/day	Sensible heat flux Wh/m²/day	Bowen ratio[c]
Mean global value	2,463	1,888	575	0.30
Bitumen Roof[a]	1,950	123	1827	14.85
Green roof[a]	2,057	1,185	872	0.74
Gravel roof[b]	2,132	687	1,445	2.10
Green roof[b]	1,800	1,258	542	0.43

[a]UFA-Fabrik Berlin, 4th June until 31st August, 2000. Precipitation 201.4 mm. Mean global radiation 5,354 Wh/m²/day
[b]Neubrandenburg, 26th April until 8th July 2004. Mean global radiation 4,848 Wh/m²/day
[c]Bowen ratio: ratio of sensible to latent heat in this context, when the magnitude of this ratio is less than one, a greater proportion of the available energy at the surface is conducted to the atmosphere as latent heat than as sensible heat, and the converse is true for values greater than one

These measured values can be used to calculate the retention values of typical green roof projects in comparison with standard roofing systems.

In Block 6, in Berlin-Kreuzberg, a system was developed to collect gray water and rainwater from 120 apartments to be treated in a constructed wetland and used to flush toilets. This reduced the demands on potable water by up to 50%. The saved costs for the potable water were almost the same as the installation cost, meaning an instant return on investment [26] (Figs. 8 and 9).

Green roof research suggests retention values of NGRs are better than those quoted in the FLL guidelines. One reason for this is that overload and vegetation of green roofs were not taken into account. Consequently, more research is required here. Bearing that in mind, it should seem obvious that NGRs do have a significant impact on storm water runoff reduction and mitigation. Green roofs are an important part of "green technology." Yet green roofs should be part of a far larger sustainable development plan for the world's cities.

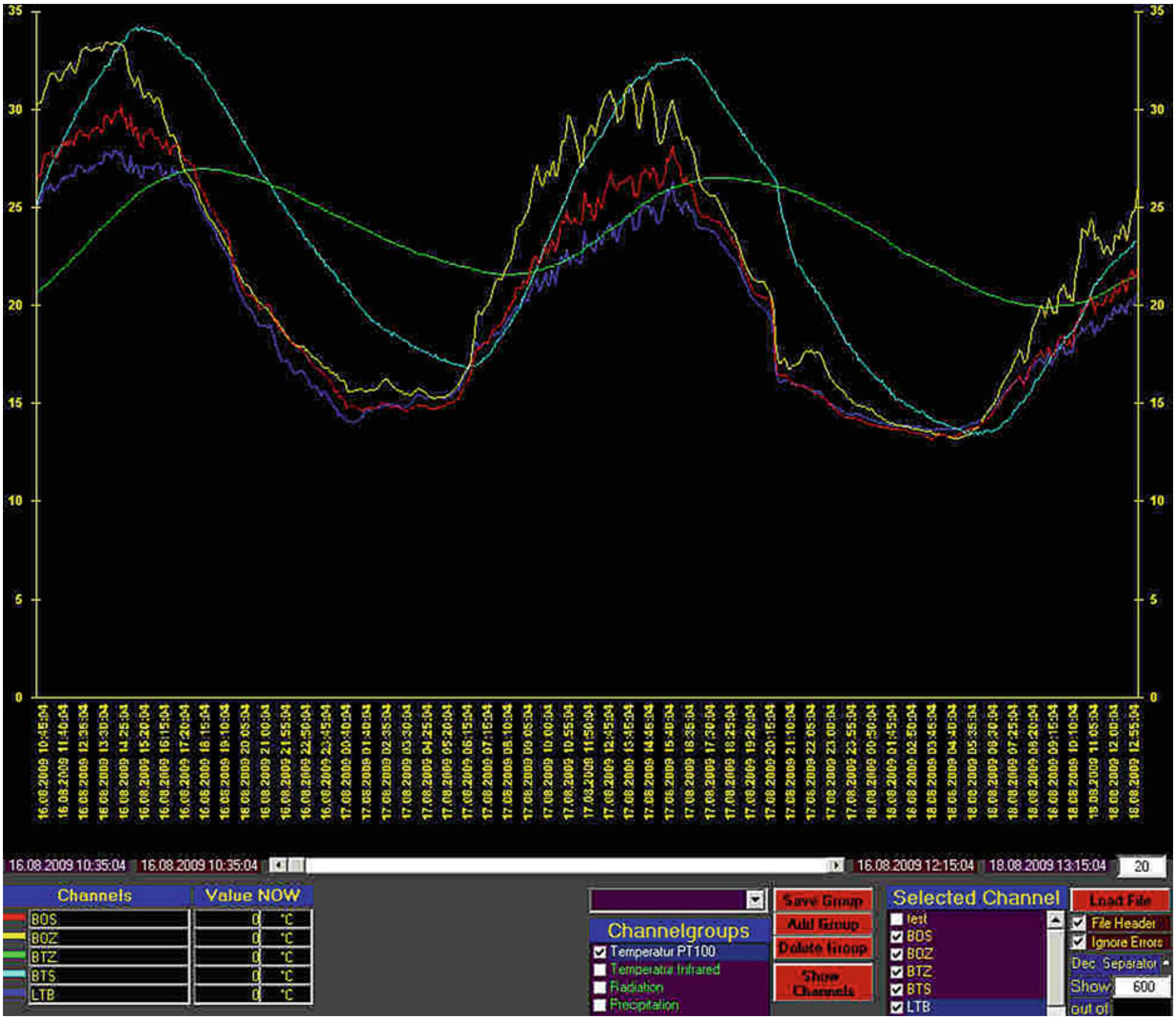
The design and implementation of green roofs specifically focusing on the aspects of rainwater management are a new issue. Green roofs should be standard elements in the calculation of water management in buildings. The data from FLL [34] and other research should be basic elements in programs to model the ecological footprint of buildings. Green roofs must be integrated into policies, regulations, building codes, and other tools for sustainability.

To encourage further understanding of the benefits of green infrastructure on urban water systems, further studies will assist in indentifying regional idiosyncrasies. Green roofs work suitably in temperate and tropic climates, but local research facilities are helpful in identifying site-specific plants and soils. Green roof technology is an interdisciplinary technology for urban water management issues – more research with a focus on civil engineering would be further supportive, like Knoll [42]. Though green roofs do offer long-term benefits, minimum maintenance is required.

A before/after impact mathematical model of an NGR as a retrofit can be seen at, e.g., http://www.sieker.de/modules/wfchannel/index.php?pagenum = 5

In the late 1970s, the German green roof industry's position vis-a-vis the irrigation of extensive green roofs was that green roofs should not be irrigated.

In the 1980s, this position changed as rain water–harvesting concepts and technologies became popular in Germany. Today, green roofs are an integrated technology in the overall rainwater management concept. Evapotranspiration on an NGR, which is irrigated during the summer in a hot country and temperate region alike using water harvested from rainwater provides significant cooling effects in combination with rainwater management. Green roofs can provide an integrated solution to many of the challenges found in the modern built environment. In addition, summer irrigation allows for greater diversity of plant species on a green roof. Yet, when the third factor of biodiversity is added to tailored solutions, it may be desirable to reduce irrigation (see "Biodiversity and Green Roofs"). What is becoming apparent is that green roofs can provide highly sophisticated solutions to many



Green Roofs, Ecological Functions. Figure 3
Real summer surface and subsurface temperature performance over 3 days, 16th to 18th of August 2009 (Example of a screenshot of the measurements in Neubrandenburg x-axis: Temperature in 5° steps, from 0°C to 35°C Temperatures: *Green line*: temperature under the substrate *Dark blue line*: Air temperature at 1 m *Light blue*: underneath *Gravel yellow*: Surface *gravel Red*: surface *Green roof*

seemingly intractable problems faced by cities and green roofs are infinitely fine tunable to achieve very specific aims.

Energy Performance of Green Roofs

The thermodynamics and thermal performance of green roofs have been studied extensively since the 1970s. The Fig. 3 explains the typical temperature values of a surface and subsurface temperatures of a gravel roof and a dry extensive green roof on three selected summer days. Remarkable is the attenuation value of the subsurface temperature of the green roof (green line, "BZT", Fig. 3). The surface temperatures of black bitumen roofs have been compared with green roofs structures. A bitumen roof surface can exceed 70°C [43]. The Research roof in Neubrandenburg, see Fig. 3, compares extensive dry green roofs with a gravel layer on non-greened roofs. This facility has a data set from a longitudinal study of about 10 years with thermal values at 5 min intervals. The graph showcases three extremely hot summer days without rain. The green line is the surface temperature underneath the growing media. The red line shows the surface temperature of the green roof. The gravel temperature is shown by the yellow line. It can be seen that the red and yellow lines follow the air temperature. The air temperature, measured in a ventilated shaded shelter, has the same peaks and troughs but at a lower level. If the growing media was damp, these graphs would be almost identical. The light blue (gravel temperature) and the green line (growing media temperature) show the impact of green roofs clearly.

Roof surface building materials are deteriorated and age through exposure to ultra violet and heat. Consequently, it is obvious that a green roof necessarily extends the life expectancy of these materials.

Furthermore, the thermal performance of green roofs in terms of summer cooling and winter insulation, which reduces building energy requirements will obviously become more and more important as the depletion of finite energy resources continues. Germany has instituted strict energy-saving policy in recent decades, and green roofs have spearheaded this drive. [43] calculated the additional insulation effect of a 10-cm layer of growing media. The result was a reduction in energy consumption during winter months in Central Europe, equivalent to that achieved by an extra 1 cm conventional insulation. The thermal impact of green roofs depends on the building being studied. Parameters such as roof/wall juxtaposition are important. A detached house with standard insulation achieves an energy saving equivalent to a "week of free heating." In light of increasing energy prices, this is an important additional benefit [43]. Also in Vancouver, a total heat flow reduction up to 70% was measured for 30 days in a moderate spring [44].

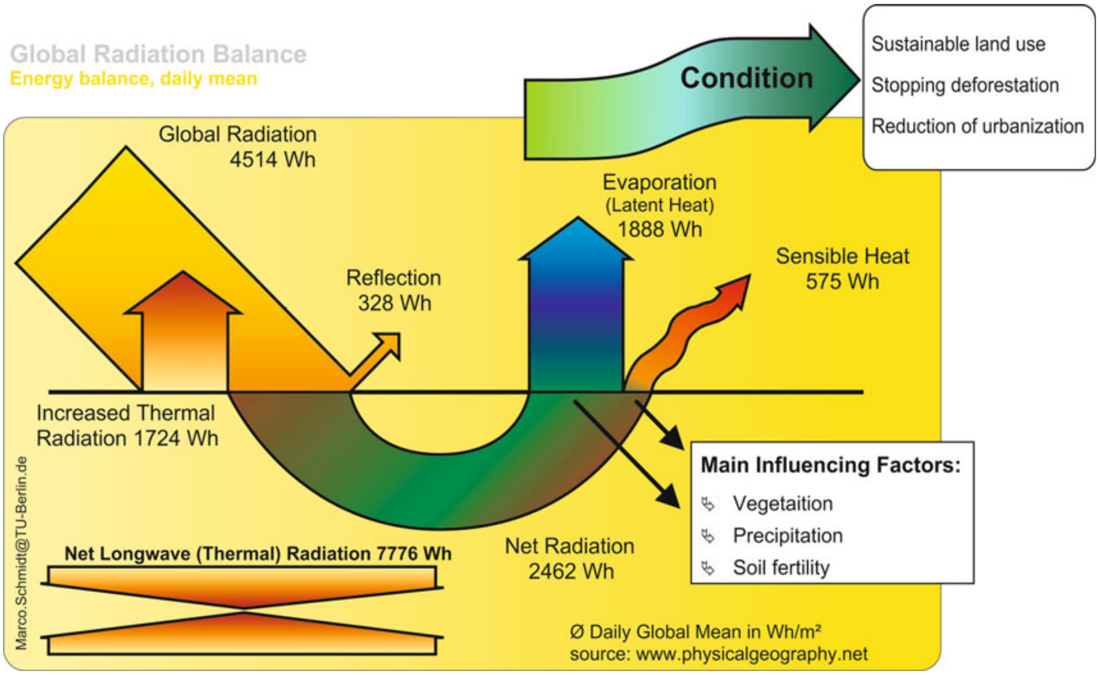
Green roofs really come into their own in the summer in reduced air conditioning requirements. Air conditioning use in Europe is on the rise, so this benefit of green roofs could reverse this trend. The *"Report on Energy Efficiency and Certification of Central Air Conditioners"* [45] of the European commission is a good database concerning the development of the air conditioning market in Europe. In recent years, energy consumption for heating has decreased due to the use of insulation and other energy efficiency strategies. During the same period, the use of air conditioning increased at a rate of 12% per year in Germany. In Germany, an increase in energy consumption for cooling and ventilation of 260% is estimated until the year 2020 [31]. In stark contrast to this, the "climate protection program" of the German government set the target for fossil fuel use reduction at 40%. This ambitious goal is mainly based on the reduction of energy consumption in the building sector.

The poor energy efficiency of air conditioners driven by electricity further contributes to the problem. Cooling a room through electricity releases an even higher amount of energy outside of the building. This approach to cooling contributes to a further increase to the urban heat island effect. However, such an approach is not necessary, because an alternative exists.

On a global scale, evaporation of water is the largest and most important component for the conversion of solar radiation. It is also the largest hydrological component together with precipitation. Only water that evaporates causes rainfall. The evaporation creates a large and small water cycle of condensation and precipitation [31].

Figure 4 shows how global radiation components are converted on the surface of the earth. The data shown represents one square meter. The diagram shows that 328 Wh (7.3%) is reflected, and 1,724 Wh (38%) is directly converted to thermal radiation due to the increase of surface temperatures. The total long-wave or so-called thermal radiation consists of the atmospheric counter-radiation and the thermal radiation of the surface. The net radiation can either be converted into sensible heat or consumed by evaporation, which is the conversion into latent heat. At 1,888 Wh/(m^2d), the energy conversion by evaporation is most important, even more important than the thermal radiation. Additionally, the evaporation influences the thermal radiation due to the change in surface temperatures. The atmospheric counter-radiation of 7,776 Wh is a theoretical component and can be considered as an exchange of long-wave radiation between two surfaces.

Heat flux data were taken at the study green roof in Neubrandenburg. Similar research was conducted by Karen Liu in Canada [44]. Both of these studies show



Green Roofs, Ecological Functions. Figure 4
Global daily radiation balance as annual mean [31]

that the heat flux in the summer is greater than in the winter. Consequently, the cooling effect of green roofs in the summer is even more important than the insulation effect in the winter.

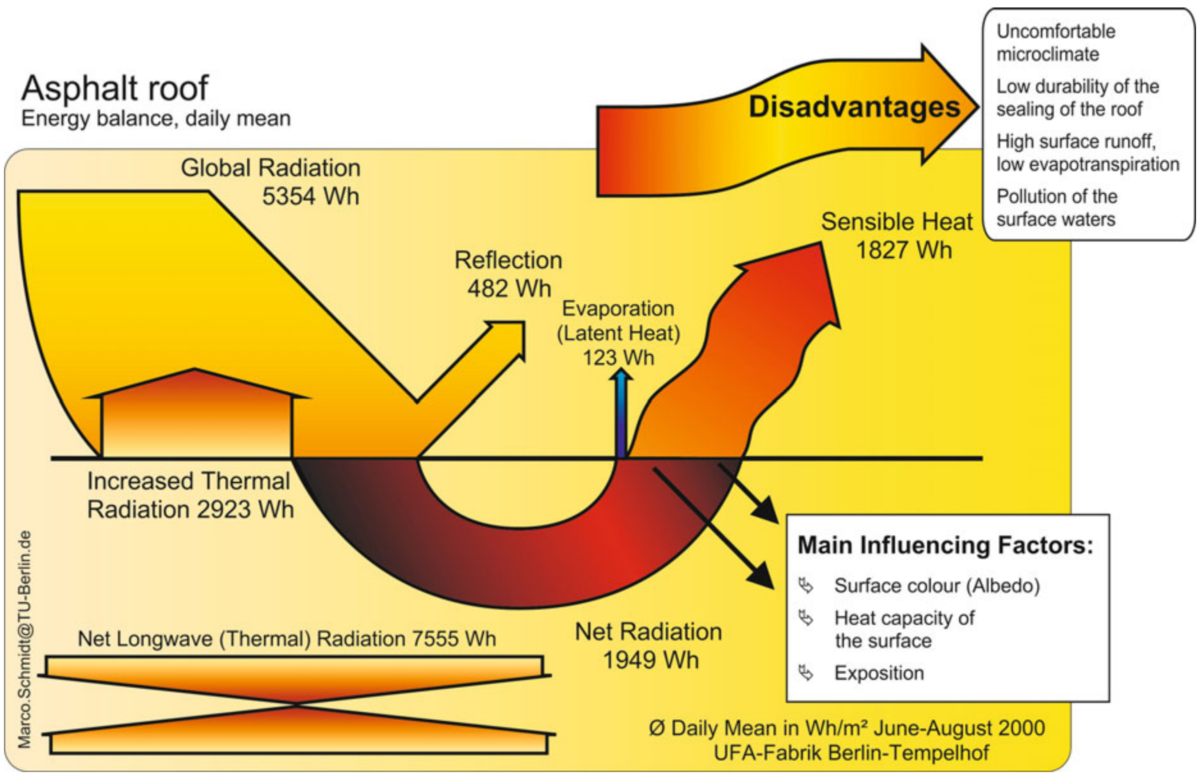
When green roofs are irrigated, the evaporation effect results in major cooling, making green roofs natural cooling systems (Figs. 4 and 5).

Conventional non-vegetated roofs have less evapotranspiration in cities. This is the reason for more direct sensible heat causing hotter surfaces at the same time. The deforestation that is occurring worldwide means losses in evaporation and higher temperatures. The two most promising ways of reversing global warming trends are urban greening and reforestation. On the global scale, the reduction in evaporation is what is mainly responsible for climate change [29 (Kravčík et al. 2007; www.waterparadigm.org)]. There is a rise in global temperatures in conjunction with increased CO_2 emissions. Both of these states are caused by reduced vegetation on the Earth and increased human development [46]. The correlation between CO_2 levels and the global temperatures represents the relation between the amount of biomass, i.e., vegetation, the photosynthesis process, and the evapotranspiration of that biomass.

The evaporation of water is the cheapest and most effective way to cool surfaces. If the rate of evaporation can be slowed, the effect is more efficient and longer lasting. This is what a green roof does. Vegetated structures evaporate water and use CO_2. Trees are the most effective cooling systems [47]. Trees must be planted in cities on a massive scale in every available space. Massive implementation of living wall and green roof technology must also be implemented.

The evaporation of one cubic meter of water requires 680 kWh of heat. Green roofs are the most efficient way to cool down a city.

Rainwater harvesting techniques, which focus on evaporation rather than storage could play a key role in further adaptation and mitigation strategies against the urban heat island effect and global warming. Green roofs and green facades have a huge potential for decreasing the environmental impact of urbanization. On a global scale, the reduction in evaporation is main cause of climate change [(see www.waterparadigm.org)]. Simulations of global climate changes still



Green Roofs, Ecological Functions. Figure 5
Radiation balance of a black asphalt roof as an example for urban radiation changes [31]

neglect the main driving factor for the global climate: the evapotranspiration of vegetation. Using evaporation, cooling for cooling purposes on green roofs and redirecting the cooling load into the dwellings mean a 41–93 higher efficiency of this energetic process than producing environmental cooling by electricity [48, 49].

Biodiversity and Green Roofs

The conditions on a roof are characterized by higher wind speed, and high direct sun irradiation. To establish vegetation on roofs, it is helpful to have higher parapet walls to protect the plants to establish the plant cover more easily. In addition, pergolas and other supporting structures help the plants grow better.

Roof gardens provide the opportunity to select shrubs and small trees. Roof gardens must be carefully designed with the knowledge of the mature heights and sizes of selected plants along with their maintenance requirements. Plants with aggressive root systems should be avoided. Bamboo is a popular plant, nowadays, which is a disaster on roof gardens because of its aggressive root system, invasive nature, and uncontrollable growth.

Roof gardens or intensive green roofs are known as "urban forestry" in Asia. A wide range of plant species are suitable for roof gardens, which fulfill the design conditions mentioned.

On the other hand, ground cover vegetation species variety is more limited. Research by Tan [49] suggested that succulent plants from South Africa are suitable for green roofs throughout the hot humid tropics. Well-selected dry adapted plant species can survive for about 49 days in the Singapore without water input from precipitation or irrigation, and some plants can go beyond this and although they look dead will recover when water comes [50].

Natural green roofs (EGR) are extreme ecosystems [51]. Many NGRs have low static loads with a shallow layer of artificial growing media of about 5–10 cm in

Green Roofs, Ecological Functions. Figure 6
Net Radio meter. Details from the research measurement facilities on a green roof at the University of Applied Sciences, Neubrandenburg, one of the Net – radiometers installed above different roof types to calculate the radiation balance

Green Roofs, Ecological Functions. Figure 8
Block 6. Plant sewer system in Berlin with rainwater cleaning facility in the back yard of a residential area of the City Center of Berlin, Details on this project can be seen at: http://www.stadtentwicklung.berlin.de/bauen/oekologisches_bauen/download/modellvorhaben/flyer_block6_engl.pdf

Green Roofs, Ecological Functions. Figure 7
Lysimeter. Detail of the roof lysimeter installation to measure the real water content of roof growing media and gravel roof

Green Roofs, Ecological Functions. Figure 9
Abb. 4. An example of a rain garden infrastructure on an intensive Green roof/Roof garden in Stuttgart

depth. After installation, they are often nearly maintenance-free. Normally, a little irrigation is used in the first year to support and encourage the initial vegetation cover. In subsequent years, only a single annual inspection is necessary to identify any maintenance needs. These needs involve mainly the removal of tree seedlings and erosion control. The vegetation will adapt to the local climate situation after a short while. It will grow to a nearly full vegetation cover without any additional irrigation and fertilizer for a long time.

Green roofs are completely man made. The negative impact of this urban ecosystem is one of the lowest of all built-up areas in cities.

About 30 years ago, decentralized oven heating emitted so much pollution, which included micro nutrients, such as sulfur and several others, that the EGRs had a good nutrition supply. When "Clean Air Policies" were instituted in cities, a nutrient deficit occurred, and a debate began within the green roof guideline commission in Germany [34] about the need for fertilizing EGRs. Poor nutrient availability is good for extreme plant species. However, added fertilizers could help to achieve a more complete vegetation cover.

The nearly zero maintenance of typical EGRs is good for wildlife as well for establishing plants, which are adapted to poor and extreme climatic conditions found on roofs with higher radiation and higher wind speed. The names for EGRs are different all over Europe, and include the following 'living roofs' 'oikosteges' "Eco roofs," "Sod roofs," or "Grass roofs." In Northern European NGRs, the percentage of grasses is higher; the modern NGR in the last 20 years is dominated by *Sedum* species in Germany.

Only a small number of plant species are suitable for extreme NGRs without any irrigation. Most of the adopted plant species have their origins on sandy dunes or poor soils and wall structures in marginal agricultural land [52]. In normal cases, it is a mixture of mosses and lichens combined with a small number of vascular plants. Succulents are one of the most well suited NGR plants. Consequently, many designers, particularly in Germany and German-influenced regions, use *Sedum* species. Specialized nurseries offer a wide selection of *Sedum* for green roofs [53,54]. But also a number of grasses can dominate such roofs, where the water storage capacity of the growing media becomes important.

The vegetation of the early period of modern green roofs constructed before the World War II was investigated by Kreh et al. [55–57]. These researchers came to the conclusion that a substrate layer of about 10 cm is suitable for a *Poetum compressa* – meadow as the climax vegetation.

Re-building and renovation work can cause damage to the vegetation and what is observed is the arrival of annual plants as biological succession begins again. Urban birds such as pigeons and doves, bring in seed of several pioneers, which will grow there for a while on the roof. The work of Darius and Drepper [57] correlated soil depth in centimeters and the successful establishment of vascular plants. This research concluded that at a depth of less than 10 cm, there will be a cover of mosses and *Sedum* in Germany. Grasses began to become established when substrate depths were 10 cm, and deeper than 20 cm substrate depths can support brown-field-grasses like *Calamagrostis epigejos*. Tree seedlings are in all cases possible, but they can only survive for extended periods if the roots can grow into cracks of the walls for a better water supply in dry seasons. So trees on the roof are, in most cases, a green roof problem as they compromise the waterproofing.

There are some 100 year old + EGRs [58]. Many of these will be removed in the coming years as these buildings are renovated. The potential value of these old green roofs is un-estimable as they are living examples of how a green roof develops and so should be protected in the same way as other natural ecosystems are protected. Research interest in such old German natural green roofs comes from outside Berlin.

At the University of Sheffield irrigation, research was conducted [59] and concluded that plant selection and depth of substrate were the vital characteristics of rich biodiversity and successful natural green roofs in the British climate. The most well suited species the study concluded were a number of Sedum species, *Festuca*, and species such as *Armeria maritima* and *Prunella vulgaris*.

In the more arid climate of Eastern Germany, the last two plant species are not able to survive on an average extensive green roofs. A 20-year longitudinal study concluded that in Berlin, for example, Chive (*Allium schoenoprasum*) was one of the most suitable species [51] (Tables 3 and 4).

To achieve a high value in local biodiversity, some aspects are important, like:

- Location (where is this project located)
- Size of the greened areas of the project
- Variation of growing media, and microhabitat
- Plant species sources in the surroundings of the project

Green Roofs, Ecological Functions. Table 3 Plant species selection for EGR

Endangered Plants, growing well on NGRs (temperate climate of Northern Europe)	*Saxifraga tridactylitis* [55 Kreh]
	Teesdalia nudicaulis
	Poa bulbosa
Some of the fittest in Central Europe	*Sedum album* and many more of the genus *Sedum*
	Cloves, many Fabaceae are good competitors on poor and dry soils
	Grasses, like genus *Festuca, Poa,*
	Allium schoenprasum
Fittest plant species in subtropics and tropics, selected after [49, 50]	*Delosperma cooperi, Cyanotis cristata, Wedelia trilobata, Liriope muscari, Ophiopogon japonicus* (This is a favorite in Germany for indoor living walls, Koehler).
	Bryophyllum "Mother of Thousands" – Crassualceae

Green Roofs, Ecological Functions. Table 4 Groups of plants, considered to be troublesome weeds, which should be removed during the annual maintenance work

		Recommendation
Tree seedlings	*Birch, Prunus, Salix, Hippopohae*	Annual inspection
Grasses	*Agropyron, Calamagrostis*	
Herbs	*Taraxacum,*	
Mosses	Several taxa, removal needed, must be discussed in relation to the project aims.	

– Age of the project, young projects include for the first years a high number of annual plant species, mature projects could have well-established vegetation

Ecological Synergy

A total overview of all ecological benefits of green roofs cannot be described for all regions in the same way. Table 5 summarizes some conclusions from several research projects.

Noise reduction, green roofs are also a good sound proofing technology and for this reason, they are used when there is a lot of noise like Schipol airport in Amsterdam.

Biodiversity: On the research roofs of the University of Neubrandenburg, the plant species richness has been investigated since the installation of the green roof structure in the year 2001. The experimental variables are four orientations (North, South, West, and East), two growing media, two methods of planting (seeds and pre produced lawn mats). The results of this study suggest the following: There are significant differences in vegetation development between the variable "North" and "South." On North, there are more grasses and some interesting herbs. On the South experimental roof, different species of the genus *Sedum* dominate. Grasses are reduced to a very few individuals.

Furthermore, over a period of the first 7 years, a significant difference between the turf mat installation and the *Sedum*-seeded area was observed.

The seeded roof developed higher species richness. The species richness of the preproduced turf mats decreases over this time [65].

Green roofs have become a topic of great research interest by a plethora of disciplines. There are about 500 peer-reviewed publications as of 2010 in various disciplines (a M. Kohler survey with Springerlink and similar data bank systems).

One interesting recent study focused on the topics: Do green roofs affect the quality of the water discharged during a storm event? Can this water be used? [66]. The answer to this question is that it depends on a number of factors. One important conclusion is that the additives used by the construction industry will become scrutinized more carefully in the coming years. Green roofs can remove numerous heavy metals from rainwater.

– The cooling effect of green roof systems must be studied extensively in the various regions of the World. Fang [67] worked on the conditions of Taiwan with climate chamber experiments. The conclusion of this study stated that a thermal reduction of surface temperatures between 20% and 60% was possible depending on the depth of

Green Roofs, Ecological Functions. Table 5 Main ecological effects of Green roofs [60, updated]

			Monetary efficiency	Source	Private/ public good
1	Insulation, Winter, Central Europe,	3–10% better than a gravel roof, 100 m^3 gas reduction each year for a single house	40.0 €/Building	Köhler (2009) [60]	Private
	Winter, southern Europe,	Depending on the type of building, no effect	–	[61] Spala	Private
2	Air can substitute summer	Insulation effect and evaporation cooling of about 3 l/m^2	Up to 20% reduction, depending on the climate in upper level of a multistorey house	[62] Alcazar	
3	Urban climate	Cooler surfaces in summer, better insulation	Monetarization, done by Banting et al. in Toronto. A green roof calculator exists on www.greenroof.org under development	[63] Banting	
4	Noise reduction	Test facilities are installed in Vancouver	A reduction of about 5 dB(A), depending on structure, moisture, and some more	[64] Maureen	
5	Biodiversity	Biodiversity depends on various factors	No monetary effect	[65] Kö Baltimore	

the substrate, its moisture content, and the vegetation type and amount of coverage.

- The thermodynamic performance of NGRs in Greece is now being studied by the Metsovio National Technical University of Athens. They have studied the oikostegi installed on The Greek Treasury in Constitution Square in Athens, opposite the Greek Parliament. They concluded among other things that the oikostegi has significantly altered the thermodynamics of the 10-story building. http://www.oikosteges.gr/index.php/green roofs/research.
- Binding fine particles is another benefit of green roofs, which is currently being studied. Yang [68] conducted research in Chicago. He concluded that an area of about 20 ha of green roofs can capture about 1,675 kg/m^2 10 particles each year. Gas born emissions, like ozone and NO_x, can be sequestered at of about 27% of total emissions.

Research interest in the subject is growing around the world. Moreover, mathematical and computer modeling algorithms are also improving leading to sound data and conclusions, which can be used to support this exciting emerging technology.

Future Directions

At Climate conferences, like the last one in Copenhagen in November 2009, participants are searching for solutions regarding how to mitigate climate change. There will not be only one strategy. But it is a truth that global deforestation and the ever increasing levels of urbanized land all over the world need strategies to increase the amount of vegetation wherever it is possible. The quality of an "urban forest" in street canyons and on the surface of buildings is not the same. From the perspective of biodiversity, only a selected number of species are able to survive on shallow substrates. So weight must be give to endemic species.

The increasing number of urban surfaces offers opportunities for urban gardening and to establish specific vegetation, in some cases, also for some endangered plant species. Roof vegetation is an engineered system, which offers benefits, as described in this entry. Better insulation against cool and hot temperatures, rainwater management, and longer lasting roof surfaces all provide monetary benefits for the property owner and all citizens. Finding the best technical solutions requires environmental specialists who understand natural ecosystems in conjunction with construction experts. As this technology grows, developments will be made, which will further improve the benefits [18]. Green roofs organizations and associations are now found in more than 30 countries worldwide. In many of these countries, academics are doing research into green roofs. Green solutions have become the hot subject of the twenty-first century. This is certain to continue as climate change begins to affect our everyday lives. Green roofs offer a way forward, which gives hope that sustainable technology is not only desirable but also very feasible. The further direction is to combine sustainable technologies and materials to enhance the number of plant species and ecological cycles on green roofs. The technical term "Natural Green Roof" will challenge urban planners in coming years. Green roofs are a fixed main and integrative element of sustainable architecture. It is cross-disciplinary subject, which is both simple and at the same time high tech. Much more growing media and plant species are possible. Also many more architectural solutions are possible [69]. It is also a two-way learning opportunity for an exchange between industrial countries and developing countries alike. In this direction, green roofs play an integrative role in rain water savings and management [70]. Green roofs provide a protection layer against temperature extremes, which provide energy-saving opportunities worldwide.

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Indoor Environmental Quality and Health Improvement, Evidence-Based Design for

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Article Outline

Glossary

AIA (The American Institute of Architects) The AIA has been the leading professional membership association for licensed architects, emerging professionals, and allied partners since 1857.

Cfm (cubic feet per minute) A non-SI (non-International System) unit of measurement of the flow of a gas or liquid that indicates how much volume in cubic feet passes by a stationary point in one minute. The ASHRAE standards and guidelines give ventilation rates for the IEQ in a specified number of cfm/person. 1 cfm = 0.472 L/s.

EBD (evidence-based design) The process of basing decisions about the built environment on credible research to achieve the best possible outcomes.

Health A state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity.

HVAC (heating, ventilation, and air-conditioning system) The systems used to provide heating, cooling, and ventilation in buildings.

IAQ (indoor air quality) The air quality within buildings, related to conditions around buildings and structures, and its relationship to the health and comfort of building occupants.

IEQ (indoor environmental quality) Beyond IAQ to encompass all aspects of the indoor setting including air quality, thermal, visual, and acoustic quality. Focuses on the strategies and systems that result in a healthy indoor environment for building occupants.

WHO (World Health Organization) A United Nations agency that coordinates international health activities and aids governments in improving health services.

Definition of Evidence-Based Design

Evidence-based design (EBD), as defined by the Center for Health Design [1], is "the process of basing decisions about the built environment on credible research to achieve the best possible outcomes." EBD is an approach to facilities design that treats the building and its occupants as a system and gives importance to design features that impact health, well-being, mood and stress, safety, operational efficiency, and economics. To date, EBD has been applied primarily to healthcare facility design, where it has been shown to frequently reduce costs, improve staff productivity, and decrease the length of patient hospital stays. The evidence-based designer, in collaboration with the informed client, develops appropriate solutions to the individual design project based on the needs and expectations of the client, research on similar projects, and experience [2]. EBD provides data on successful strategies for the design process for healthy, high quality buildings.

Introduction

Concepts

Healthy, high-performance buildings should have positive outcomes in terms of energy, sustainability, health, and productivity. A healthy building should meet the World Health Organization (WHO) [3] definition of health, "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". The use of this definition of health is particularly applicable to green buildings, intent on not only reducing exposures to chemicals, but also promoting exercise, lowering stress, increasing social interactions,

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and otherwise fostering physical, social, and mental health for the occupants. EBD not only meets the WHO health definition, but also encompasses productivity, operational efficiency, economic performance, and occupant/customer satisfaction. Effective EBD needs to be combined with sustainable design, incorporating all practices that reduce the negative impact of development on ecological health and indoor environmental quality [4].

Sustainable, creative design features for application of EBD fall into four major categories, which impact health, economic performance, and operational efficiency of the building system:

- Innovative building enclosures that incorporate load balancing, natural ventilation, and daylighting
- Advanced HVAC systems that incorporate natural conditioning, increased environmental contact, and local control
- Innovative data/voice/power "connectivity" and individual control
- New interior system designs in workstations and workgroup designs for improvements in spatial, thermal, acoustic, visual, and IAQ parameters [5]

Innovative enclosures and advanced HVAC systems particularly impact IAQ, health, productivity and learning, stress reduction, and operational economics. Innovative connectivity and new interior system designs chiefly impact health both as physical well-being and social well-being via connectivity to the organization as a whole, stress reduction, and health.

Indoor Environmental Quality

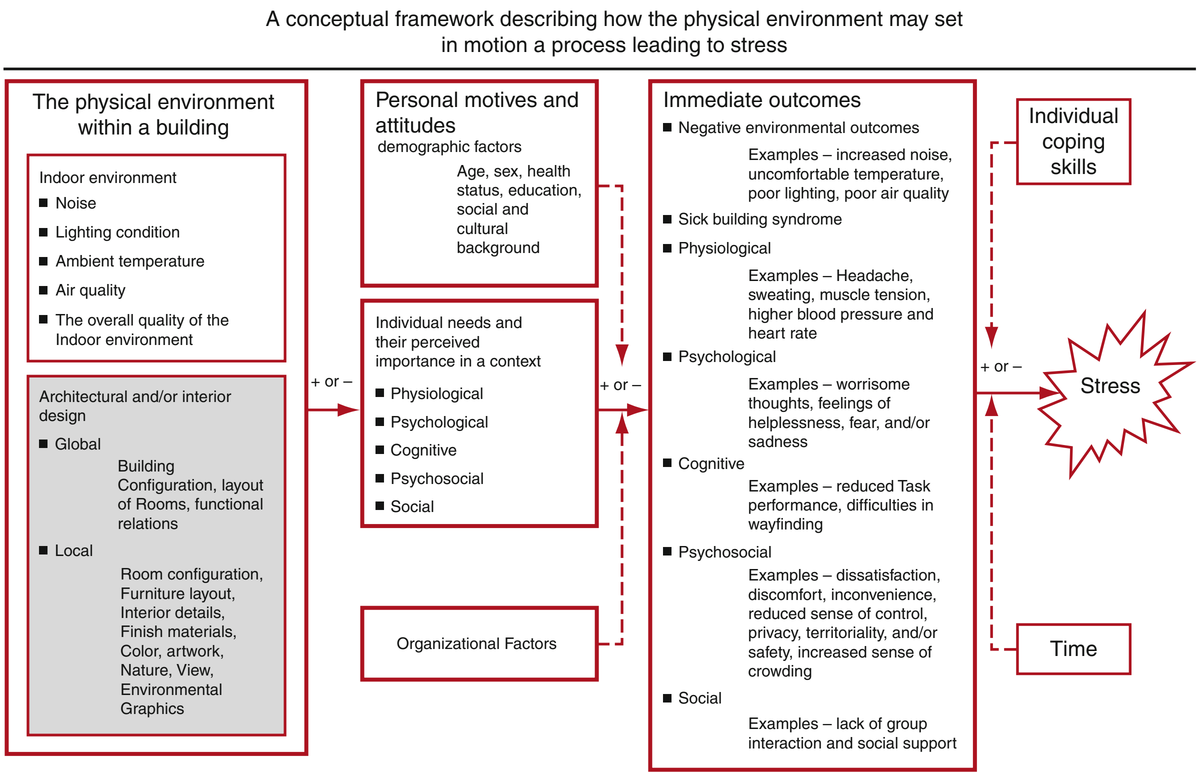
Healthy buildings encompass all aspects of indoor environmental quality (IEQ) including optimum thermal comfort, lighting with effective daylighting and access to views, IAQ, acoustical performance, ventilation effectiveness integrated with natural ventilation when applicable, and human comfort and health. Healthy buildings are designed for ease of operation and maintenance, because buildings with inadequate IEQ adversely impact occupants' overall health and productivity.

Rashid and Zimring [6] suggest that poor indoor environments may initiate a process leading to stress whenever the individual or workplace IEQ does not meet an occupant's needs, as is shown in Fig. 1. Their framework groups physical environmental variables into two primary groups: (1) IEQ variables including noise, lighting, ambient temperature, and IAQ, and (2) interior design variables including use of space, furniture, fixtures and equipment, finishing materials, color, artwork, natural views, and environmental graphics. These variables are interlinked in the design of the indoor environment and its conditioning systems. Factors leading to stress, similar to individual responses to odors, vary among individuals, further complicating the issues [7]. The collaboration between the designer and the user in the EBD design process is critical in reducing stressors in the indoor environment.

Examples of potential environmentally induced stressors that need to be assessed in the EBD process are:

1. Open office plans creating feelings of lack of privacy [8]
2. Open office plans, selection of hard-surfaced flooring and furnishing materials, office equipment location, HVAC system vibration, and/or or outdoor traffic that may increase noise levels resulting in difficulties in concentration, speech intelligibility, headaches, and other physical and emotional stress responses that impact learning and productivity [9–11]
3. Cafeteria, cleaning, furnishings, or systems odors permeating throughout the work areas of a building due to improper ventilation system design or poor materials selection [12, 13]
4. Daylight glare on work surfaces due to lack of effective window glazing or absence of blinds, and unshielded electric lighting that may result in headaches or eyestrain and poor productivity [14–16]

The Academy of Neuroscience for Architecture (www.anfarch.org) is using evidence-based design as a means to assess the linkage between neuroscience research and human responses to the built environment; thus seeking to relate behavioral changes to brain function changes based on the built environment. The Academy, in its studies, defines the dimensions of functional comfort as: (1) air quality, (2) thermal comfort, (3) spatial comfort, (4) collaborative or teamspace, (5) visual comfort, (6) workstation comfort, (7) lighting quality, (8) noise control, and (9) security. These nine parameters are used to direct the



Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 1
Rashid and Zimring [6] conceptual framework describing how the physical environment may initiate a process leading to stress

evidence-based design practices to reduce human stress, poor behaviors and attitudes, and overall human health, as defined by WHO.

Indoor Air Quality The primary design strategies that are used to improve IAQ in green buildings are the use of low-emitting furnishings and building materials, designed to meet an iteratively tightening set of standards [17–20]. This strategy addresses one of the most important IAQ determinants that is clearly in the realm of the designer – source control. However, the construction process, including installation sequence and protection of materials prior to installation, is also an important factor to be addressed by the EBD team. Installation of carpet prior to painting of walls can result in long-term low level emissions of paint fumes due to adsorption by the carpet and slow reemission into the indoor environment. Key furnishing and material sources that must be specified as low-emitting and eco-friendly include office furniture, flooring, paints and coatings, adhesives and sealants, wall coverings, wood products, textiles, insulation, and cleaning products. The potential adverse health impacts of pollutants that may emit from these products has been determined though many emissions investigations [21].

Another strategy available for reducing exposures to airborne contaminants is source control of indoor equipment and activities. Office machines, stoves, and other appliances that are known to be active pollutant generators benefit from the use of local source control via the installation of dedicated exhaust fans. The use of local source control systems needs to be part of the design process and the location of the areas needing dedicated ventilation and exhausts need to be defined early in the design process. The use of well-maintained air cleaners is another strategy that may be appropriate to selected areas and types of facilities, such as in hospitals.

Ventilation systems are the primary method to dilute and transport airborne contaminants out of the building. Natural and mixed-mode systems, if employed, must be designed to provide sufficient pollutant dilution and transport out of the building.

Ventilation System Design/Environmental Control The ventilation system is the primary means of transporting contaminants into, throughout, and out of the indoor environment. The placement and design of the system is critical to the quality of the indoor environment. Superior ventilation has been shown to improve learning, productivity, satisfaction, and health. At the same time the ventilation system can transport unwanted outdoor pollutants indoors, transfer indoor pollutants from one space to another, or transport infections [22].

In most buildings, the ventilation system is linked to the thermal conditioning (temperature control) system. Combined thermal comfort and ventilation systems may inadvertently compromise ventilation potentially adversely impacting IEQ, health, and occupant satisfaction. If a decision has to be made between thermal comfort and ventilation response, EBD reveals that the lack of temperature control is a primary stressor in the indoor environment, impacting productivity, learning, mood, and overall health [23].

On the other hand, lower temperatures, especially when combined with increased ventilation rates, tend to increase productivity and student performance. Wargocki and Wyon found that lowering the classroom temperature approximately 5°C improved elementary school students' performance on two numerical tasks and two language-based tasks [24, 25]. The children also reported lower incidence of headaches. When the classroom effective outdoor air supply rate was raised from 11 cfm/person (5 L/s) to 20 cfm/person (10 L/s), the students' performance was improved on four numerical tasks by improving the task performance speed. The children also reported feeling that the air felt fresher with the lower ambient temperatures. Similar results on the relationship of temperature and ventilation on productivity have been reported in adult work situations [26–29]. As a result, EBD reveals the importance in the design of the environmental control/ventilation system of separating the ventilation system from the thermal conditioning system and providing the ability for occupants to individually control the ambient temperature.

Numerous studies show health, productivity, and learning improvements with higher ventilation rates; however, this must also be balanced with sustainable design for greater energy efficiency through the use of innovative ventilation systems and maximizing ventilation efficiency. Haverinen-Shaughnessy et al. [30] found a linear association between classroom ventilation rates within the range of 0.9–7.1 L/s/person and students' academic achievement. In this study of fifth graders, it was determined that for every unit (1 L/s/person) increase in the ventilation rate, the proportion of students passing standardized tests increased by 2.9% for math and 2.7% for reading. Studies have shown that occupants in buildings or spaces with higher ventilation rates on average have fewer communicable respiratory illnesses, and lower asthma rates, and fewer absences from work or school [30–32]. The European Multidisciplinary Scientific Consensus Meeting (EUROVEN) [32] found that ventilation is strongly associated with perceived air quality and health (sick building syndrome symptoms, inflammation, infections, asthma, allergy, short-term sick leave) and that there is an association between ventilation and productivity in offices. The EUROVEN group also concluded that outdoor air supply rates below 25 L/s/person increased the risk of sick building syndrome symptoms, increases in short-term sick leave, and decreased productivity among occupants of an office building. Additionally improper maintenance, design, and functioning air-conditioning systems contribute to increased prevalence of sick building syndrome symptoms.

The research clearly demonstrates significant associations between ventilation system design that allows increased levels of ventilation, at least 10 L/s per person of outdoor air supply in buildings for optimized health, productivity/learning, and reduced stress. In order to meet sustainable design practices meeting the goal of energy efficiency and reduced operating costs, innovative ventilation strategies and systems must be used. Natural ventilation and hybrid systems are important innovative approaches, to be combined with next generation active systems.

Lighting/Daylighting/Access to Views Studies have shown that daylighting has a positive impact on humans, improving accuracy of work performance, reducing stress and fatigue, and improving patient outcomes [32]. Loftness et al. [14] found that improved lighting quality design decisions are linked with 0.7–23% gains in individual productivity. The lighting quality design ranged from indirect–direct lighting systems, higher quality fixtures, and daylighting simulation. When daylight responsive dimming was employed energy savings of 27–87% were realized.

Access to the natural environment is associated with individual health and productivity. Design decisions for exposure to views include access to windows and view, daylighting through windows and skylights, natural and mixed-mode ventilation systems, and direct accessibility to landscaped indoor and outdoor spaces. Access to the natural environment has been shown to result in 3–18% increases in individual productivity [14] including access to operable windows.

Evidence from school lighting research indicates that improved school lighting can enhance both visual (healthy vision) and non-visual (achievement outcomes). Lighting conditions in classrooms have important non-visual effects on students including potentially raising test scores and faster responding on tests [33].

Acoustics/Noise Control Acoustics is an area of continued dissatisfaction in many green buildings [9]. In a number of projects, the open plan design, large areas of glass, hard-surface materials and furnishings, and natural ventilation strategies used in many green buildings have led to ongoing concerns with acoustic conditions. Building acoustical problems are generally classified in three categories: excessive noise, lack of speech privacy, and lack of speech clarity. Excessive noise is usually the result of high background noise emanating from outdoor noise sources that are transmitted through to the indoor environment, as well as noise from other rooms, building equipment, and/or noise from other occupants. Acoustical design strategies need to control noise levels at the source, reduce sound transmission pathways, and employ sound isolation techniques. Speech privacy is the extent to which speech is unintelligible to an *unintended* listener. The worst speech privacy situations are those where the background noise is very low. In open office plan environments, the lack of speech privacy may be a significant stressor. Design strategies to help improve speech privacy include possibly reconsideration of the open office plan, designing private areas adjacent to the open office area for use in private situations as needed, or increasing background noise. A lack of speech clarity occurs when the acoustics or a room design deteriorate the acoustical communication channel, rendering speech to the *intended* listener unintelligible, creating communication problems. This is particularly an issue in school classrooms and conference rooms. The problem may be caused by excessive background noise or excessive reverberation. EBD solutions to improve acoustics while maintaining sustainable design strategies include the use of acoustically absorbing materials, such as ceiling absorbers, acoustical ceiling tiles or wall-mounted panels.

Operation and Maintenance

A critical area that EBD needs to address for long-term building sustainability and occupant health is designing for maintainability. The life-cycle costing must include the maintenance and operating costs over the facilities lifetime, and EBD feedback on the long-term integrity and maintainability of the materials, components or systems. Metrics should be defined during the design process for the ability to maintain the facility in order to meet health and client economic performance needs. These metrics, at a minimum, should include:

- Labor hours per year that will be required to maintain each integral part of the facility, such as the HVAC system(s), the electrical system, lighting, windows, skylights, floors, and furnishings
- Frequency, extensiveness, and difficulty to perform required cleaning (including avoided toxicity)
- Cost of cleaning and replacement materials
- Equipment and furnishings life expectancies
- Training costs in labor hours and dollars for maintenance staff and occupants/building users

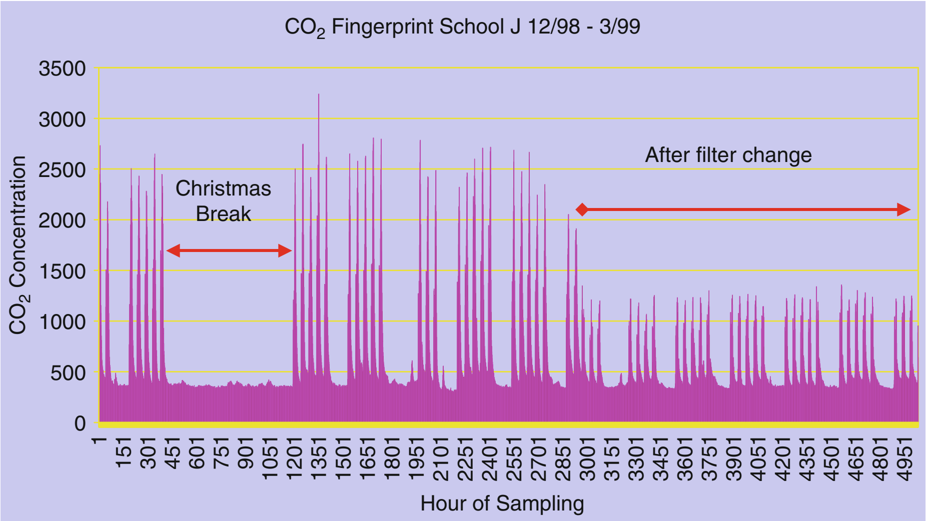
Magee [33] defined the specific maintenance objectives of the majority of facilities as follows:

- Perform necessary daily housekeeping and cleaning to maintain
- Promptly respond and repair minor discrepancies
- Develop and execute a system of regularly scheduled maintenance actions to prevent premature failure of the facility, its systems, and/or components

- Complete major repairs based on lowest life-cycle costs
- Identify and complete improvement projects to reduce and minimize total operating and maintenance costs without increasing indoor toxicity
- Operate the facility utilities in the most economical manner that achieves reliability and optimum functioning, while minimizing or eliminating indoor toxicity
- Provide for easy and complete reporting and identification of necessary repair and maintenance work
- Perform accurate cost estimating to ensure lowest cost and most effective solutions
- Maintain a proper level of materials and spare parts to minimize downtime
- Actively track all costs of maintenance work
- Schedule all planned work in advance allocating and anticipating staff requirements to meet planned and unplanned events
- Monitor progress of all maintenance work
- Maintain complete historical data concerning the facility in general and equipment and components in particular
- Continually seek workable engineering solutions to maintenance problems

Maintenance has a considerable impact on a building's performance and upon occupants' health and satisfaction. Maintenance-related problems over a building's lifetime can be minimized by making appropriate design decisions early in the process.

For example, maintainability is a critical measure for the performance for all ventilation systems including innovative high-performance ventilation systems and may have a significant impact on the health of the building occupants. In a study conducted by Bayer et al. [34] on the benefits of active humidity control and continuous ventilation at a minimum level of at least 15 cfm/person in schools using high-efficiency total energy heat recovery desiccant cooling ventilation system, the importance of system particulate filter maintenance was clearly demonstrated. As can be seen in Fig. 2, the carbon dioxide (CO_2) concentrations in the classroom exceeded 2,000 ppm during occupied times in the classrooms prior to replacement of the particulate filter in the system. Once the filter was changed, reducing the impedance to outside air delivery, the CO_2 levels dropped to approximately 800–1,000 ppm during occupied periods of the classroom. This result clearly demonstrates the necessity of system maintenance for effective ventilation even when a high-efficiency ventilation system is employed. In this school, filter replacement was inadequate due to difficulty in accessing the filter for replacement, a design and maintenance flaw.



Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 2
CO_2 levels demonstrate the importance of particulate filter maintenance for effective ventilation in an occupied classroom

Maintaining the cleanliness of the ventilation filters has been found to impact productivity and learning in office buildings and schools. Wargocki et al. [35], in a study on the performance and subjective responses of call-center operators, found that replacing a used filter with a clean filter reduced operator talktime by about 10% at a outdoor air supply rate of approximately 34.4 L/s, but no effect was noted when the filter was replaced and the outdoor air supply rate was only 34.4 L/s. Additionally the operators reported a decrease in sick building syndrome symptoms with clean filters and the increased ventilation rates.

These investigations clearly demonstrate the importance of filter changeouts and ventilation system maintenance for IEQ, health, and productivity. The building systems need to be designed for easy performance of ventilation system maintenance tasks.

Arditi and Nawakorawit [36] surveyed 211 of the largest US building design firms to investigate the relationship between design practices and maintenance considerations. The study examined the extent to which maintenance issues are considered when designers specify building materials and service equipment; the level of designers' knowledge in maintenance-related issues; the degree to which design personnel are exposed to training in maintenance-related matters; the extent to which designers consult property managers and maintenance consultants; the relative importance of maintenance issues to other design factors; the level of difficulty in cleaning, inspecting, repairing, and replacing various building components; and the magnitude and frequency of maintenance-related complaints that designers receive from clients and tenants. Their findings indicate that maintenance consideration follow cost and aesthetics issues when designers specify building materials, but maintenance considerations constitute the number one issue when specifying service equipment. For most firms, the mechanical system was considered to be the most important consideration with regard to difficulty of cleaning, inspection, repair, and replacement with both the designers and the property managers. However ease of repair and replacement, access to cleaning area, and ease of cleaning were ranked by designers to be among the least important design factors for building systems and the facility. This in spite of the fact that the primary complaint that designers reported receiving from clients and tenants concerned issues of ease of repair, access to cleaning area, and ease of cleaning. Property managers also reported frequently receiving similar complaints. The design firms considered themselves to be knowledgeable in maintenance issues and design, and stated that they consulted property managers and maintenance consultants during the designing of selected projects, primarily in the schematic and preliminary design phases.

This is an area where EBD demands increased collaboration among all of the interested parties throughout the entire design process. EBD maintenance planning and design will enhance the life-long performance of the building.

Human Factor Impacts/Occupant/Customer Satisfaction on Sustainable Designs

Many sustainable design strategies reduce the use of walls and partitions – with more open space planning – to reduce material use, enhance views and daylight, and increase ventilation airflow, particularly when natural and hybrid ventilation strategies are used. Although this may increase satisfaction with daylight and access to views, it may also increase dissatisfaction with noise, privacy, and the ability to concentrate [37]. This situation was encountered in the LEED Platinum certified Philip Merrill Environmental Center in Annapolis, MD [38]. This facility placed the entire workforce into an open plan setting, regardless of status in the company, including the president and the key executives, without doors and low partitions for almost all employees (Fig. 3). This allows access to views and daylighting for all employees and the occupants' satisfaction ratings are very high. However, the primary complaints that remain are lack of privacy, noise, distractions, and interference with work concentration. At the same time, the occupants rated the views, daylighting, and interactive behaviors and communication highly.

Evidence-based design is an effective strategy for determining the potential effectiveness of open space planning in different types of buildings and task situations [39, 40]. For example, an elementary school in Atlanta, GA, organized in pods, uses four-foot high partitions among lower grade classrooms in each pod rather than floor-to-ceiling walls to increase interaction between grade classes. The partition heights

Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 3
Open floor plan at Philip Merrill Environmental Center. Picture available at http://www.cbf.org/Page.aspx?pid=445

Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 4
Open classroom style at Atlanta, GA, elementary school

increase as the grade level increases until in fifth grade (Fig. 4), the traditional classroom style is used. Staff interviews expressed mixed attitudes about this open design style. Noise between classrooms is a problem; however, as with the Philip Merrill Environmental Center, there was satisfaction with the feeling of community between the grade levels [41]. What has not been sufficiently studied at the school is the potential interference with student concentration in a school with an open floor plan such as is used in this school. The use of the lower partitions in the lower grade levels is actually the converse of what is needed for optimum acoustical performance for learning. Younger children in K-2 grades require a higher signal-to-noise ratio (clearer voices in a quieter environment) since they need to be able to carefully listen to develop the ability to discriminate among minor differences in words, which is extremely difficult in noisy environments [42].

Application to Healthcare Facilities

Hospitals are embracing evidence-based health care design for the promotion of therapeutic, supportive, and efficient environments. EBD is undertaken to develop appropriate solutions to design problems and unique situations in order to improve the organization's clinical outcomes, economic performance, efficiency, and customer satisfaction. EBD helps to provide solutions to the healthcare challenges of cost control, financial stability, avoidance of harm, quality improvements, sustainability, staff retention, and improved patient experience.

Ulrich et al. [43] reviewed the research literature on EBD healthcare design. Their overall findings indicated the importance of improving patient outcomes through a range of design characteristics including single-bed rooms, effective ventilation systems, good acoustical environments, increased views of nature, improved daylighting and interior lighting, better ergonomic design, acuity-adaptable rooms, and improved floor layouts and work settings. A number of significant results were found by optimization of environmental measures through the design process.

EBD can help eliminate hospital-acquired infections through better control of the three most significant vehicles for transmission: air, contact, and water. The most important design measures for infections controls are: (1) effective air quality control measures during construction and renovation using high-efficiency particulate air filters (HEPA) filtration and installation of barriers isolating construction areas (minimize airborne transmission); (2) installation and use of alcohol-based handrub dispensers at the bedside and other accessible locations (minimize contact transmission); (3) easy to clean floor, wall, and furniture coverings (minimize contact transmission); (4) water system maintained at proper temperatures with adequate pressure to minimize stagnation and backflow (minimize waterborne transmission); and (5) single-bed rooms with private toilets for better patient isolation (minimize airborne and contact transmission).

Medical errors may be reduced through control of several environmental factors including noise, light, and acuity-adaptable single-patient rooms. Noise, both as unacceptable background and episodic interruptions, is responsible for loss of concentration, slower learning, and poor memorization. Additionally excessive noise adversely impacts patient recovery by increasing stress and interrupting sleep. Lighting levels impact task performance, which in a hospital may result in transcription errors [44]. Conversely, better lighting and daylighting design results in improved patient care and outcomes, staff satisfaction, safety, and decreased operational costs [45]. The acuity-adaptable rooms have adequate square footage in the room to accommodate several clinical activities without moving the patient, well-defined zones for patient care activities, strategic placement of handwashing sink and handrub dispensers, convenient access to medical supplies, headwalls designed with adequate critical care services, maximum patient visibility, and patient lifts to ease strain on staff. Another desirable feature is a family zone so that a visitor is able to stay with the patient comfortably [46] (Fig. 5).

Studies are showing that patient pain levels and length of hospital stays can be reduced by exposure to nature and exposure to higher levels of daylight [47]. Walch et al. [48] found that spinal surgery patients in bright daylight lit rooms required 22% less opioid-equivalent analgesic medications than those in rooms without the bright daylight. Beauchemin and Hays [49] found that myocardial infarction patients in bright daylight lit rooms had shorter hospital stays of at least a day shorter. Ulrich [50] showed that surgery patients with views of nature had reduced hospital stays and used lower levels of pain medicine. EBD reveals that providing patients with high levels of daylight and views of nature (even if only pictures of nature if access to actual outdoor views are not possible) offers an opportunity to reduce patient pain medicine use and length of hospital stays, improving overall patient outcomes.

Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 5
Acuity-adaptable, well-lit hospital rooms improve patient care and staff satisfaction

Reduction in ambient noise levels has been shown through EBD studies to improve patient sleep and reduce patient stress [51, 52]. For example, studies have shown reduced wound healing with exposure to noise, primarily attributed to increased levels of stress [53, 54]. EBD strategies that are applicable to noise control in hospitals include single-patient rooms, use of high-performance sound absorbing materials (although these must be easily cleanable), reduced noise from carts in the hallways, and noiseless paging systems.

EBD has led to improvements in staff workspace design as well as in patient care. EBD reveals that staff workspace needs to be designed with closer alignment to work patterns to improve staff satisfaction, productivity, and reduce stress reduction, which in turn will improve patient outcomes [38]. Potential design features may include decentralized nursing stations, more efficient layouts that allow staff interaction with patients and family members, and decentralized supply locations. Early EBD studies also reveal that the location of family members near the patients may also improve patient outcomes and reduce hospital stay lengths [55].

Economic Performance

Salaries and worker benefits generally exceed energy costs by approximately a factor of 100 [56]. Healthy, high-performance sustainable buildings that are based on EBD principles have a strong potential to have positive economic performance, as long as the EBD design principles meet the organizational and health needs of the users as well as sustainable design principles. Therefore, a significant potential exists for businesses and building owners to employ EBD principles that improve worker performance, improve health, reduce health insurance costs, and reduce absenteeism.

Heerwagen [57] examined the range of benefits of green building features and attributes in buildings. She found that

- Green buildings are relevant to business interests across the full spectrum of concerns, from portfolio issues to enhanced quality of individual workspaces.
- Outcomes of interest that research should address include workforce attraction and retention, quality of work life, work output, and customer relationships.
- Green buildings can provide both cost reduction benefits and value added benefits.
- The benefits are most likely to occur when the building and organization are treated as an integrated system from the initiation of the design process, as in Evidence-Based Design approaches.

The Carnegie Mellon Center for Building Performance and Diagnostics (CBPD) and the Advanced Building Systems Integration Consortium have developed a decision support tool (The Building Investment Decision Support Tool – BIDS) to enable building decision makers to calculate returns on investments in high-performance building systems and to advance the understanding of the relationship between land use and buildings and health [56]. BIDS is based on a collection of building case studies as well as laboratory and simulation study results to statistically link the quality of buildings. BIDS uses "soft" and hard life-cycle costs to calculate the return on investment. The diverse building-related costs in the USA, including salaries and health benefits, technological and spatial turnover, rent, energy, and maintenance costs, normalized in dollars per person per year, are shown in Fig. 6.

Using statistics from the Bureau of Labor Statistics, the CBPD [56] calculated that the average employer health insurance cost was approximately $5,000 per employee per year in 2003. The CBPD went on and linked the cost of several specific health conditions and illnesses to IEQ (colds, headaches, respiratory illnesses, musculoskeletal disorders, and back pain), which account for approximately $750 of the $5,000 annual costs per employee – 14% of all annual health insurance expenditures. These direct costs would be additionally multiplied by the indirect costs of lost productivity. The results from employing BIDS provide the impetus to demonstrate the financial benefits of using EBD to design better building environments.

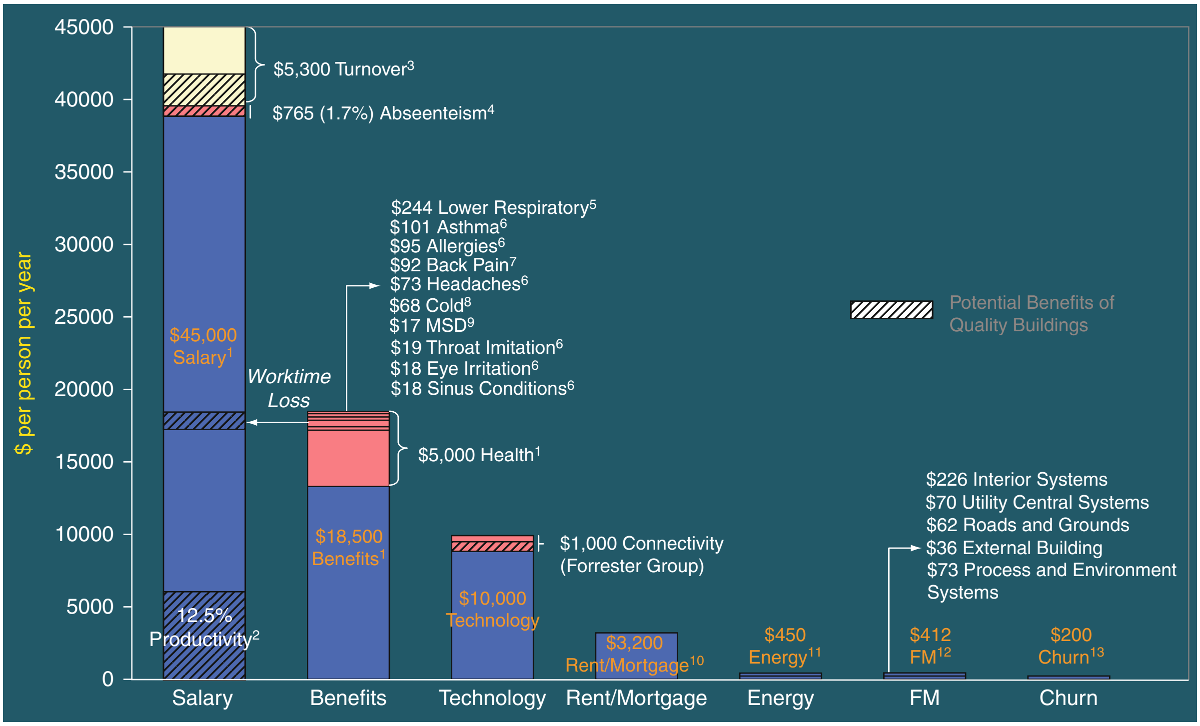
Fisk and Seppanen [58] demonstrated a benefit-cost ratio as high as 80 and an annual economic benefit as high as $700 per person when measures are made to improve indoor temperature control and increased ventilation rates based on a review of the existing literature of the health linkages between temperature control and increased ventilation rates. Table 1 shows the estimated productivity gains as a result of four categories of sources.

Application to Other Types of Facilities

The in-depth studies to support EBD in healthcare settings are readily adaptable to other types of facilities, particularly K-12 schools, including methods for infection control, better lighting, access to views and daylighting, improved acoustical performance, interior workspace layouts, and community design. The application of EBD in conjunction with sustainable design should result in optimal facilities for learning, healthcare, and work with maximum emphasis on human and ecological health as well as economic performance.

Schools

The impact of environmental design on the educational performance of students in the UK was investigated by Edwards [59]. In this study, Edwards investigated if "green" schools provide teaching and learning benefits beyond those in conventional schools, and what aspects of classroom design appear to be most critical in improving enhanced educational performance. Green schools were defined as being resource efficient particularly in terms of energy use; healthy both physically and psychologically; comfortable, responsive, and flexible; and based on ecological principles. In the study of



Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Figure 6
The true cost of least-cost buildings in the USA (US baselines from CMU BIDS) [50]

Indoor Environmental Quality and Health Improvement, Evidence-Based Design for. Table 1 Estimated potential productivity gains [58]

Source of productivity gain	Potential annual health benefits	Potential US annual savings or productivity gain (1996 US $$)
Reduced respiratory illness	16–37 million avoided cases of common cold or influenza	$6–14 billion
Reduced allergies and asthma	8–25% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	$1–4 billion
Reduced sick building syndrome symptoms	Health symptoms experienced frequently at work by ~15 million workers	$10–30 billion
Improved worker performance from changes in thermal environment and lighting	Not applicable	$20–160 billion

54 schools built between 1975 and 1995, it was demonstrated that there is relationship between design, energy conservation, and educational performance. Overall the study demonstrated that green schools resulted in enhanced student performance and greater teacher satisfaction with the greatest impact on elementary schools. Benefits were greater in the newer schools with higher levels of ventilation. Absenteeism was reduced in the green schools. The student performance improvement appeared to be particularly related to the

level of daylight in the classroom, but also the level of ventilation, the temperature control, and noise level controls.

Elzeyadi [60] conducted a study to develop the Green Classroom Toolbox with green design guidelines for retrofitting existing educational spaces. The guidelines are based on carbon neutrality metrics and student achievement metrics, developed from a meta-analysis of reported studies and energy modeling simulations. The guidelines center on best practices that increase productivity, comfort, and health of students in retrofitted classrooms; facilitate integrated design and cooperation between designers; reduce environmental impacts and move toward carbon neutrality environments in schools; and are a model for future replication and dissemination. The strategic categories relevant to building professionals are based on the USGBC LEED criteria (1) energy and atmosphere (envelope, lighting, HVAC, and ventilation); (2) materials and resources (site construction, structural, and nonstructural); (3) environmental quality (IAQ, comfort, and acoustics); (4) sustainable sites (density, light pollution, and transportation); and (5) water and waste (building fixtures, landscaping, and recycling). Elzeyadi's method examined the facility as a whole system. He used a framework that treated the students and the school environment as interdependent elements of a system. The system is comprised of "people" and "buildings" on the macro-scale and "buildings" and "environment" on the megascale. This study resulted in three primary decision support tools of evidence-based guidelines to help architects, school designers, and school/school system staff to make informed decisions for implementing green retrofit measures in classrooms. The first tool is a check list of best practices compiled from focus groups and interviews of affected and interested parties. The second tool is a prioritization guide that provides a comparative analysis and ranking of the best practices list (in Tool 1) based on their impacts on building energy consumption and carbon emissions. The third tool is a meta-analysis guide that links the Tool 1 best practices to their impact on student and staff health and performance in schools. All of the tools were based on the specific climates and school typologies of the Pacific Northwest in the USA. The primary reason found for adoption of the best practices in schools was energy conservation followed by providing improved IEQ and connections to nature, reflected in energy and atmosphere, IEQ, and materials and resources gains. Better IAQ, based on the meta-analysis, was found to positively impact occupants' performance in a range of 5–20% improvement. This included reduced illnesses, both chronic and acute, and improved performance on testing. Improved temperature control was found to improve student performance in the range of 3–10%. Access to views and daylighting improved student performance in the range of 5–20%. This study emphasizes the need for evidence-based design guidelines for schools, especially to focus on improving IAQ, improved temperature control, and access to views and daylighting. The manner in which the study was conducted simulates the evidence-design process – interaction between the designers and the users, studying best practices and strategies in other successful facilities, and implementing the practices expected to have the most positive impact based on all of the stakeholders needs.

Office Buildings and Other Types of Facilities

The Academy of Neuroscience for Architecture has applied evidence-based design practices to office building design – focusing on the previously enumerated parameters (1) air quality, (2) thermal comfort, (3) spatial comfort, (4) collaborative or teamspace, (5) visual comfort, (6) workstation comfort, (7) lighting quality, (8) noise control, and (9) security. In their office building study [61], conducted via post-occupancy questionnaires, it was found that the office design features that support security, wayfinding, and feeling part of a cohesive organization created increased satisfaction and "workability" (considered to be neuro-environmental factors) among the employees over their previous office space. This was hypothesized to result in reducing stress, improving attention, focus, and mood. The office space design features included a centralized three-story open stairway connecting the three office floors, providing a naturally mapped sense of place, a "public square" housing centralized communications and meeting areas, a main entry area, centralized lunchroom, well-labeled directional signage, and use of porcelain tile paving across primary transit areas.

The Academy of Neuroscience for Architecture [62] also conducted a limited intervention study exploring the potential applications of neuroscience concepts and evidence-design based methods to correctional facilities. The specific focus topics were (1) daylight and views, (2) exposure to nature, (3) space size, (4) ambient noise levels, (5) color, and (6) environmental design features and their impact on inmate–staff relationships – reducing stress and aggressive behaviors. The overall goal of the study was to develop evidence-based design decisions for correctional settings and operations. The results of this study seemed to indicate that views of nature was the most effective measure of stress reduction, even if they were only projected nature views on a wall.

Future Directions

It is critical that EBD be applied much more widely across the spectrum of buildings. EBD has a tremendous potential to set a new paradigm for designing healthy, sustainable buildings, by including the building managers and occupants as a central player in the entire system's resolution of ecological and human health.

Even in the limited time that evidence-based design has been embraced, the data demonstrate important shifts for the building design and management community. For example, the need for increased ventilation rates significantly above those currently being used in the majority of buildings demands the development and implementation of innovative solutions that simultaneously meet reduced energy usage and cost. These include systems that separate ventilation and thermal conditioning, and new HVAC system types, such as underfloor air distribution and chilled beams. These also include improvements in system maintenance, such as the application of the ASHRAE Indoor Air Quality Procedure (IAQP) employing gaseous phase filtration to aid in air cleaning so that the ventilation level can be reduced. Ongoing research in more effective technologies and systems management is critical.

Future research must also include the development of protocols and metrics to accurately and realistically measure human impact improvements in health and productivity/learning, operational efficiencies, and sustainability. These metrics must consider the entire system in the occupied setting and not a just a single unit of the system. Metrics in specific will greatly aid in providing the necessary parameters for effective EBD studies in a wide range of buildings.

In the future, disparities between sustainable design practices and EBD will need to be resolved. Many practices are fully concurrent, but there are still areas where there is conflict, such as lack of acoustical satisfaction in open office planning and the potential energy costs of higher rates of ventilation for improved health and productivity/learning.

EBD takes the first step in rigorous research of "real" buildings by actively engaging in feedback through occupant questionnaires, and pursuing multi-configuration studies (in the form of layout or building system variations) or multi-building studies for comparative evaluation by end users. The lack of consistent feedback from building occupants and managers in the building design community has led for far too long to anecdotal design decision making, either in the form of untested shifts (such as open classrooms) or a dogged commitment to the status quo. EBD is an invaluable step forward, employing a range of post-occupancy tools – both qualitative and quantitative – to develop design innovations for human and environmental and economic benefit. EBD does not eliminate the need for controlled experimentation, both in the lab and in the field, to advance innovations in building materials, components, and systems design and operation.

Summary/Conclusions

The use of Evidence-Based Design to improve the IEQ in buildings has the potential to significantly impact the total health, productivity, learning, operational efficiency, and economic performance of a facility and its occupants. To begin with, a wide variety of studies have shown the importance of a connection to nature through access to views and daylighting to reduce stress, improve patient outcomes, improve health, and increase productivity. In the available literature, this connection to nature may be the most important design feature for overall impact studied to date. Secondly, an improved, innovative ventilation system has been shown to be critical to improving health and productivity in buildings, of at least 25 L/s per person. Thirdly, the separation of temperature control from the ventilation system is another important component for improving thermal comfort without compromising ventilation air delivery. Finally, acoustical control is one of the most challenging parameters for EBD innovation, yet critically needed to achieve occupant satisfaction, stress reduction, and optimum learning in schools. EBD combined with sustainable design principles is an important tool for retrofitting and designing healthy, high-performance buildings.

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Landscape Planning for Minimizing Land Consumption

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Article Outline

Glossary

Development plan A document (often consisting of several written documents and maps) that aims at organizing the spatial development in a particular territory in a comprehensive manner; the term development plan has different meanings in different legal and administrative contexts, in many countries it is used for indicative rather than compulsory plans that complement land use planning by addressing additional aspects of spatial development (e.g., infrastructure planning).

Density, urban density Urban densities are measured by the number of people (or housing units, floor space, jobs) per unit urban land (e.g., km, hectare, acre); density is an important measure of urban form; the density of a lot, a neighborhood, or city usually indicates the intensity of urban land uses.

Green belt Idea of retaining an area of largely undeveloped, agricultural, or wild or park land surrounding an urban settlement.

Greenfield development Urban development that occurs on previously nonurban (agricultural, forestry, pasture, or other) land (as opposed to brownfield development that occurs on derelict sites); synonym of land consumption.

Growth management A set of policies and interventions used by governments at different tiers to ensure that urban growth occurs in a controlled and sustainable way; the containment of urban growth to counteract urban sprawl, the sufficient supply with urban services, and the protection of valuable land resources are the most important aims of growth management programs.

Land consumption Conversion of land use from nonurban (agricultural, forestry, pasture, or other) to urban uses (mainly residential, industrial, commercial, and transport); the term has a pejorative connotation.

Land cover The observed biophysical cover on the earth's surface, usually expressed in terms of vegetation cover or lack of it; land cover changes can occur as the conversion from one class of land cover to another or as a changing condition within a land cover class.

Land use Human employment of land; land use is characterized by the arrangements, activities, and inputs undertaken by humans in order to use land for productive or reproductive purposes; urban land use change can be attributed to the change of use from a land use class to another or to varying intensities within a land use class.

Land use pattern Spatial configuration of land uses or patches.

Land use plan Product of land use planning that is usually legally binding and prescribes how a piece of land can (and how it must not) be used.

Land use planning Any systematic effort of public authorities to organize (or at least influence) the way people, that is, society, make use of the land.

Spatial planning Any systematic effort of public authorities to organize, that is, influence the pattern of spatial organization of society. (Spatial planning is often used as a synonym of land use planning but can be seen as the broader term that also includes sector-specific planning, e.g., the planning and allocation of infrastructures.)

Suburbanization Suburbanization occurs when the growth of the suburbs (population, employment)

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dominates that of the central city; suburbanization is driven by relocation decisions of private households and firms leaving the central parts of metropolitan areas in favor of suburban, less dense, and cheaper lands; at the same time, suburbanization can also be caused by in-migration from outside the metropolitan area to the suburban parts.

Urban design plan A specific kind of land use plan, which, according to the planning system of many countries, formulates detailed norms for the land use of smaller areas (e.g., a couple of building blocks); urban design plans are often drawn up for areas that are about to be developed or fundamentally restructured.

Urbanization An increase in the proportion of the population living in urban areas or cities (urban systems).

Urban sprawl A specific, mostly unintended, pattern of land use that exhibits low-density residential and commercial settlements, the spatial segregation of certain land use types in specialized zones, and a spatially discontinuous urban expansion; in metropolitan areas, both in developed and developing countries, urban sprawl is the dominating spatial manifestation of land consumption.

Urban growth boundary (UGB) Line, defined by land use planning, which circumscribes an entire urbanized area and mandates that the area inside the boundary is to be used for higher density urban development and the area outside for lower density development.

Urban system Human settlements with a minimum population density.

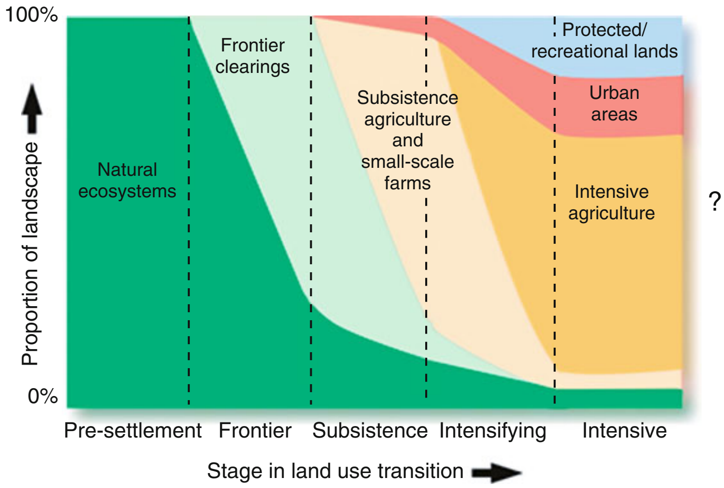
Zoning The practice of designating permitted uses of land to particular areas that are unambiguously separated from each other; zoning is usually enacted via land use plans and primarily aims at segregating uses that are thought to be incompatible.

Definition and Relevance of the Subject

Land use-driven environmental degradation has long been considered a locally scaled phenomenon. Today, the global dimension of land use related environmental change is generally acknowledged by researchers and policy makers [1–4]. The need to provide a still growing world population with housing, food, fiber, and freshwater accompanied with wasteful land use practices has resulted in a cumulative loss of biologically productive land and ecosystem functions. Moreover, land use practices are directly or indirectly responsible for the chemical degradation of environmental resources and high levels of greenhouse gases. Thus, land use has become a more and more important agent of global change that influences fundamental environmental processes. Foley et al. [1, p 572] rightly point out that modern land use processes allow humans to increase the short-term supply of material goods but undermine ecosystem services in the long run on regional and global scales.

Urbanization or – more specifically – land consumption as the conversion of land use from nonurban to urban uses is only a part of land use-driven environmental degradation processes. And it may not be the most important one with respect to the loss of productive land and ecosystem services. Between 0.3% and 4% of the earth's land surface is occupied by impervious or built-up surfaces [2, 4–7]. The pervasive effects of forest clearance, subsistence agriculture, and intensified farmland production are perhaps more important for the ongoing loss of the world's biological resources (Fig. 1). However, when taking the many indirect impact pathways of urban land uses into account (e.g., fragmentation of natural landscapes and habitats, chemical degradation of hydrological systems by polluted urban runoff, roads affecting adjacent habitats by noise), urbanization must be regarded as an important causative factor in models of global and regional environmental change [8].

In addition, there are strong links between urbanization levels and the intensity of rural land use, be it through land-consuming urban lifestyles (tourism and recreational activities, second homes), the relocation of unwanted land uses to the city edge or even peripheral locations (airports, wastewater sites, etc.), or the demand for facilities that serve the increased intensity of production and energy flows between rural and urban communities (transport infrastructure, warehousing, biofuel production, solar parks, wind parks). Land consumption goes against the objectives of sustainable development in two ways: (1) by increasing the ecological footprint through the addition of land with resource consumptive human activities and (2) by reducing the biocapacity of a region or a country.



Landscape Planning for Minimizing Land Consumption. Figure 1
Stages of land use transition in human history [1]

At the same time, blaming land consumption for urban purposes as environmentally harmful and generally non-sustainable would be an inappropriate simplification. The phenomenon of urban growth confronts human societies with an intrinsic dilemma. On the one hand, the continuous development of land for residential or commercial purposes is absolutely essential for demographically and economically growing nations [9]. On the other hand, land-consuming human activities degrade ecosystem services upon which demographically growing societies strongly depend. Adding to the dilemma, land-intensive modes of urban growth often represent people's preferences for greener, less dense, and automobile-oriented communities.

While global land use change has become a hot topic over the past few years, urbanization, suburbanization, and urban sprawl at regional and local scales have been the subjects of long-standing academic discussions. Over the years, improving standards of living, the increase in personal mobility, the industrialization of agriculture, the ongoing land demand by households and firms, together with vast changes in societal norms and values have led to widespread conflicts over the use of land [10]. Land consumption changes the physical performance of urban systems in a variety of ways. Among them, the increase in artificial surfaces, the change in densities, and the alteration of land use patterns are the most important ones. Land consumption is being blamed for its contribution to the degradation of natural and seminatural habitats and its stimulating effects on motorized transportation. Consequently, concerns have arisen on the role of changing urban forms for rising greenhouse gas emissions and climate change [11–13]. Moreover, in the recent past other impacts attracted consideration, such as the negative implication of low-density environments on physical activity levels and health outcomes (e.g., [14]).

Recent policy initiatives have further fuelled interest in this subject. In the USA, a number of states have adopted growth management programs that aim at containing urban growth and preserving valuable open space. The English government has set a national target to deliver 60% of all new housing units on previously developed land and through conversions of the existing building stock. The government regards the reuse of urban land a key policy to reduce the development pressure on the open countryside and to improve urban regeneration by upgrading physically and socially deprived cities and neighborhoods with new housing and urban services of higher quality [15]. The Chinese government, concerned about the alarming loss of prime farmland due to urbanization, has introduced regulative policies that aim to protect farmland more effectively [16]. The German federal government introduced a national target to reduce the rate of conversion of nonurban to urban land uses from 130 ha per day in 2000 to 30 ha per day in 2020 [17]. The government argues that land consumption and landscape fragmentation, important aspects of "urban sprawl," are to be acknowledged as key drivers of species loss, landscape deterioration, and the decline of infrastructure efficiency.

While the effectiveness of these legislations and policy initiatives is subject to a highly controversial dispute (e.g., [18–21]), their sheer existence has stimulated further research into the nature of urban expansion patterns, their environmental, social, and economic impacts, and more effective anti-sprawl strategies and policies.

Introduction

Public concern over the undesirable effects of urban growth and land consumption can be traced back to an era when the "exploding metropolis" and its radically changing land use patterns and urban design first became physically visible. The beginning suburbanization process at a metropolitan scale was accompanied by an unprecedented expansion of development at the expense of open space and natural land resources. Not surprisingly, the debate on the unintended effects of urban growth started in the USA where rising affluence, a rapid motorization, public funds for low-density housing, and an antiurban social climate ("white flight") had formed the precondition for a "mass movement" from the central cities to suburban areas – much earlier than in Europe or other parts of the world. In a 1937 speech to US urban planners, Earl Draper, Director of Tennessee Valley Authority, first used the term "sprawl" to indicate a specific pattern of urban growth that makes the countryside – from his point of view – "ugly, uneconomic [in terms] of services and doubtful social value" (cited from [22]). Since then, the discussion about the impacts of urban sprawl as well as its drivers and remedies has continued (see [23–27] as early contributions) and spread around the globe. Today, urban sprawl and its counterpart, the "compact city," are subject to scientific and political discourses in many developed *and* developing countries (see [28–34] as a few more recent examples).

This debate has clearly broadened its scope and increased in intensity over the decades. The major topics that characterized the debate on urban sprawl before the 1980s had already been established before the Second World War, notably the effects on ecosystem services and landscape beauty, on transportation and the efficiency of network infrastructure [35]. In the last two decades, however, researchers have made substantial progress in empirically addressing spatial manifestations, drivers, and effects of land-consuming human activities as well as the effectiveness of anti-sprawl policies and instruments. As a consequence, the global dimension of land consumption and urban sprawl (as noted above) is now on the agenda of policy makers and researchers worldwide.

Despite the fact that we know much more about the nature of land consumption and its complex societal roots today, many research questions still need to be addressed. On the one hand, it can be said that the quality of information regarding past trends in land use change has significantly improved over the decades, mainly due to the availability of new data sources like remotely sensed data. Likewise, thorough knowledge has been acquired on the many different and complex impacts of land consumption. On the other hand, forecasting future land consumption remains a scientific challenge. Current state-of-the-art prediction models often have to deal with unreliable data, their use is therefore limited to the definition of alternative scenarios within the ranges of uncertainty. In addition, there is still considerable scope for the deepening of scientific knowledge on the driving forces and dynamics of land-consuming developments [36, p 45f].

Apart from these methodological and conceptual challenges, the lack of internationally comparative data on urban land use prevents scientists from analyzing the influence of region-specific political and cultural factors on the spatial formation of urban growth. In this context, research on urban sprawl is largely limited to case studies of selected metropolitan areas in a national context that have limited value for the comparison of regional policies or housing preferences. While economic and population trends are often subject to international cross-sectional research efforts and are therefore well-documented, virtually no information exists on the amounts, rates, and patterns of urban expansion across countries and their metropolitan areas. It has only been in the recent past that empirical studies systematically addressed similarities and dissimilarities in urban land use change across world regions and countries [2, 8, 37–39].

Based on this problem description, this contribution aims to provide a comprehensive overview on the debate on land consumption and its importance for related thematic fields in spatial planning, that is, urban and regional planning as well as environmental and conservation planning. It starts with an elaboration of the meaning of "land consumption" in terms of terminology, causations, and consequences (Section on "A Conceptualization of Land Consumption"). Then, it provides an account of how spatial planning can try to control land consumption, thereby introducing a taxonomy of planning strategies and instruments that appear suited to minimize land consumption (Section on "The Means of Spatial Planning to Minimize Land Consumption"). The contribution concludes with a brief outlook on future challenges regarding both planning practices as well as scientific efforts that endeavor to get a grip on land consumption, either in reality or conceptually (Section on "Future Directions").

A Conceptualization of Land Consumption

What is Land Consumption?

Land consumption, sometimes referred to as land take [38, 40, p 308] can be regarded as a subprocess of land use change marked by a conversion from nonurban to urban land use types. The visible outcome of land consumption is the spatial expansion of built-up areas accompanied by a significant alteration of land cover features and urban form. The construction of new buildings and infrastructure facilities, the sealing of surfaces and other modifications of the original land surface usually result in a decline of environmental quality. Clearly, it is not land that is consumed. The term "consumption" solely refers to the mostly irreversible loss of ecosystem services (or even entire ecosystems) due to the physical modification of land cover.

In terms of environmental significance, the size of urban areas by itself would be a very poor indicator for the impact of urban land use [6]. In order to adequately address land consumption in terms of its negative (or positive) effects in this context,

- The previous use of land and land cover (agricultural, forestry, or natural)
- The dominant purpose of new urban use (residential, commercial, industrial, recreational, or others) and the corresponding land cover features such as the imperviousness of surfaces
- The location and pattern of new urban land and
- The efficiency of land use

have to be taken into account [8]. To put it bluntly, the development of an acre or hectare of new residential land on former agricultural land has not the same impact as the development of an acre or hectare of industrial land on a drained wetland site. New development in the vicinity of existing settlements has clearly fewer negative impacts on the landscape matrix than the development of many small and disconnected patches throughout the open space (often referred to as "scattered sprawl" or "leapfrogging"). Therefore it is not only the quantity of land converted to urban uses that needs to be considered, but also the spatial patterns and their flow-on effects on environmental qualities that urban planning and management need to take notice of.

Fortunately, improvements in the resolution and quality of digital land use and land cover data have opened up new possibilities for a spatially more refined modeling of urban form, including measures for development patterns. In the recent past, numerous methodological approaches to provide quantitative assessments of urban form and urban sprawl have been introduced [8, 41–45]; see Chin [46] for a brief overview. Table 1 lists prominent measures (indicators) of land consumption and urban sprawl along with their function (description) and sources in the literature.

Looking at recent urbanization trends, land consumption can take very different intensities and forms. In Europe, the annual growth of urban land is expected to range between a maximum of 2% in rapidly growing areas and nearly 0% in remote rural regions [55]. For the period from 1990 to 2000, Angel et al. [2, p 56] estimated that the annual increase in built-up areas in developing countries was around 3.6%, whereas it amounted to only 2.9% on average in industrialized countries. Among the world regions, East Asia, including the Pacific, and Southeast Asia have witnessed the most intensive land consumption with growth rates of 7.2% and 6.4%, respectively.

Other studies provide empirical evidence that the spreading of urban land uses clearly exceeds population

Landscape Planning for Minimizing Land Consumption. Table 1 Frequently proposed land consumption and urban sprawl measures

Indicator	Description	Sources
Size or share of urban land	Size of urban land (km^2 or sqm); percentage of urban land (%)	[2, 8, 42, 45, 47]
New land consumption	Converted urban land (in hectares or acres)	[9, 45]
Urban density	Number of people, jobs, or housing units per hectare of urban land (gross or net)	[2, 41, 45, 46, 48–50]
Change in urban density	Change of urban density between two base years (percentage)	[2, 19, 45, 51]
Density gradient	Regression of density against distance by ordinary least-squares (OLS) means	[41, 44]
Land use mix/land use separation	Degree to which different urban land uses exist in close distance to each other (measured with indices like the Shannon Diversity Index)	[42, 44, 46, 49, 52]
Continuity/dispersion/ fragmentation/complexity	The degree to which developable land is built up continuously; the degree of irregularity of built-up patches (measured with certain indices such as the patch density or more complex statistical measures of spatial regularity)	[8, 37, 42, 45, 46]
Concentration/ decentralization	Degree to which urban development is located near to the CBD (e.g., measured with the percentage of population and employment within concentric rings around the CBD or the median person's/worker's distance in distance units from CBD)	[37, 42, 44, 50, 53, 54]

growth, resulting in declining overall densities (see, e.g., [2, 50, 53, 55–57]). In Germany, for example, per-capita land use for housing, transport, industrial, and commercial as well as recreational needs increased from 350 m in 1950 to more than 500 m in 1999 [58]. At the same time, in metropolitan areas urban density gradients have significantly flattened over time. It is worth mentioning that urban systems both in developed and developing countries have witnessed this process of decreasing densities, although it was more intense in the developed world [2]. Urban densities decreased between 1990 and 2000 worldwide, in East Asia by as much as 4.9% per annum and in Europe by a relatively moderate 1.9%.

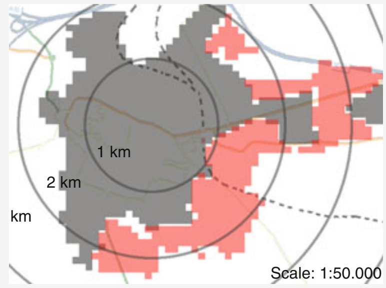
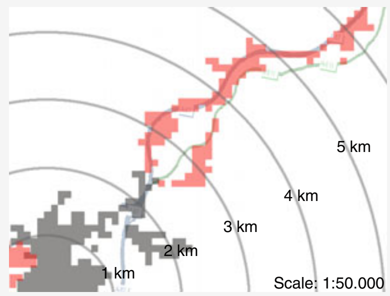
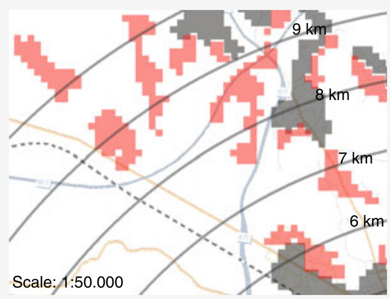
The change of spatial configurations of urbanized areas that results from the shift of private households and firms from central locations to suburban and exurban areas is another highly visible characteristic of land consumption. Over time, metropolitan areas have changed their urban form from a highly concentrated compact structure to a rather dispersed or polycentric pattern [22, 59–63]. The deconcentration of urban systems ("suburbanization") has come along with a change of micro-patterns of urban form, often addressed with terms like "leapfrogging" or "ribbon" development. In this sense, land consumption has contributed to the large-scale transformation of urban systems from a compact urban form to an irregular, discontinuous, and dispersed urban land use pattern [31, 41, 42, 52]. Table 2 presents some characteristic "real world" examples for the spatial manifestation of "contiguous," "ribbon," or "leapfrogging" urban growth.

Drivers of Land Consumption

What factors account for the phenomenon of land consumption in general? What explains regional disparities in the rates at which land consumption occurs, and why do the patterns of land use conversions differ significantly between countries and even regions (e.g., [37])? Furthermore, why does land consumption often continue under conditions of stagnation or even decline [64]?

First of all, it has to be said that an explanatory model of land consumption cannot be deduced from a grand theory of urban growth or urban development

Landscape Planning for Minimizing Land Consumption. Table 2 Types of urban sprawl (*grey colors* existing urban area 1990, *red colors* expansion 1990–2006; data sources: CORINE Land Cover 1990, 2000, and 2006, OpenStreetMap)

Types of urban sprawl	Examples
"Contiguous" or "continuous" development • New urban area is located adjacent to existing urban areas, expanding ring-wise around the central city • Structure: compact and "contiguous," possibly interrupted by topographic features • Land use: mono-functional or mixed, with residential and commercial use around subcenters, industrial along radial transport routes • Impact: flattened density gradient from the inner city to the city edge, well suited for mass transit systems, poor open space provision for inner-city dwellers	
"Ribbon" development • New urban area is located near major transport network facilities (motorway on-ramps, public transport stations) • Structure: the resulting settlement patterns resemble strips or "ribbons" • Land use: often mono-functional residential areas preferred by commuters, extensive industrial (warehousing) or commercial use (shopping malls) • Impact: habitat fragmentation, inefficient in terms of urban service provision	
"Leapfrogging" development • New urban area is located in isolated patches far from existing urban areas • Structure: dispersed and disconnected urban structures, surrounded by open space • Land use: mostly mono-functional industrial, commercial, or residential areas • Impact: relies on new infrastructure, inefficient to service with public transport and network infrastructure, fragmentation of open space; availability of nearby open space	

simply because such a theory does not exist. However, social sciences and economics have offered theories that help to identify important drivers of land-consuming human activities. In particular, neoclassical economic theory provides a closed framework for the explanation of urban growth. It argues that location decisions of private households and firms reflect the aim to get the maximum utility out of matching space needs, location preferences, and financial budget constraints. Given an unregulated land market, land rents near the urban core are highest because transportation costs are lowest and accessibility of urban services is therefore best. It is the sum of all costs within the income elasticities for land and transportation that determines location choice. High-income groups (with more land-demanding aspirations) may prefer to live in a larger distance to the city center where large building lots are available, whereas low-income households will choose a location near the urban core with lower transportation costs. Based on these primary considerations, the monocentric model of urban spatial structure explains the spatial expansion of cities and density gradients with just a few variables, namely, the demand for new housing and commercial land, rising incomes, innovations of intra-urban transportation systems, and decreasing transportation costs [65–68]. In this sense, the growing physical footprint of cities and their declining density is the combined effect of a growing population, rising affluence, and enhanced individual mobility due to the increasing affordability of the private motor car.

Critics of the neoclassical monocentric urban model ("Alonso–Muth–Mills model") claim that many other factors than land prices and commuting costs affect location decisions [35]. Examples are the quality of urban services, specific priorities, and demands of different social groups in terms of urban and environmental amenities, or the desire to live in a socially homogeneous neighborhood. The Tiebout Local Public Finance Model [69] suggests that people decide to locate in a particular jurisdiction based on their preferences and taste for local amenities. Tiebout describes factors that "pull" people out of the central areas of metropolitan regions because of attractive characteristics of suburban communities (e.g., good service levels or lower taxes) and others that "push" people out of central areas as a result of central city problems such as crime or poor environmental quality and services.

The disagreement with the Alonso–Muth–Mills model is also fuelled by the empirical emergence of polycentric urban configurations [70–72]. The outward movement of jobs is regarded as a key factor explaining this trend. Suburban and exurban industrialization, beginning in the 1950s and 1960s, have made rural areas attractive to workers as new places to live in. In contrast to the fundamental assumption in the neoclassical city model that employment concentrates in the central business districts (and gradually decreases with increasing distance to the urban core), modern agglomerations in developed countries are characterized by their multinodal settlement system with a complex pattern of primary and secondary centers.

Next to economic theories, technical and social sciences aim to explain urban growth and the change of urban form [73]. Technical viewpoints focus on the role of transport innovations in order to explain the spatial diffusion of urban land uses. They associate the compactness of the preindustrial city with the fact that most trips had to be made on foot or similarly slow modes of transportation. This constraint disappeared with the availability of faster mass transportation technologies and the private automobile [74]. Following this logic, the physical growth of cities became a function of transport technology. Nelson [21] points out that other improvements in technology such as the personal computer, cellular phones, or the Internet may have encouraged the spatial decentralization of people and firms further, setting out the conditions for more land-intensive forms of urbanization.

On the one hand, economic, social, and technical theories help to explain the intensity of urban deconcentration and the associated rate of land consumption. On the other hand, they fall short of explaining the spatial patterns of urban land development. The reasons are manifold: neoclassical theory assumes that an unregulated market exists without any regulating land use policies (e.g., land use zoning) and that biophysical factors unfavorable for urban land use can be ignored. However, it is evident that these factors of urban development need to be taken into account to understand how actual land consumption patterns result from a complex interaction between various social, demographic, economic, and environmental processes. As a consequence, spatially explicit land use models have been developed that not only explain *at what rates* land use change occurs in a given period of time, but also address the question *where* land consumption will take place, that is, the likely location of change [5, 75].

For this purpose, Poelmans and van Rompaey [5] distinguish five groups of explanatory variables that are frequently used in models of land consumption:

- Biophysical factors may have an impact on the suitability of land tracts for the construction of buildings or infrastructure facilities. For example, factors such as slope or environmental hazards strongly influence the cost of development. Therefore, biophysical factors can explain why certain areas are excluded from development.
- Social factors put emphasis on location preferences of households (or household types). Examples are the income level or ethnic composition of nearby neighborhoods and the availability of public green spaces. These factors may encourage or discourage the choice of a development site.

Landscape Planning for Minimizing Land Consumption. Table 3 Explanatory variables used in land consumption model applications (*dark grey* strong explanation, *pale grey* moderate explanation, *white* not relevant)

Factor	Examples	Explanation of rate of land consumption	Explanation of location of land consumption
Biophysical	Slope	[white]	[dark grey]
	Hazardous land	[white]	[dark grey]
Economic	Economic growth	[dark grey]	[white]
	Land prices	[dark grey]	[pale grey]
	Distance to urban centers	[white]	[dark grey]
	Distance to the main road	[white]	[dark grey]
	Fiscal motives to convert land into urban use	[dark grey]	[white]
Demographic/ social	Population growth	[dark grey]	[white]
	Income growth and changes in lifestyles	[dark grey]	[white]
	Motorization	[dark grey]	[pale grey]
	Social preferences for housing types and locations	[pale grey]	[dark grey]
Spatial policies	Land use regulation (positive and negative planning)	[dark grey]	[dark grey]
	Revitalization and renovation policies	[dark grey]	[white]
	Public funds for Greenfield development	[dark grey]	[white]

- Economic factors refer to accessibility features as proxy values for market access. Frequently used measures are the distance to urban centers or main roads and the availability of public transport services in a walkable distance. Undeveloped properties with good accessibility are more probable to become urbanized in the future.
- Neighborhood interactions refer to an observed spatial autocorrelation between new developments and existing urbanized areas. In contrast, some potentially conflicting land uses (e.g., residential and industrial development) are unlikely to be located directly next to each other.
- Spatial policies are relevant because of their influence on the location decisions of private households and firms. These policies can be labeled "negative planning" where they aim to protect current land uses (habitat conservation, prime farmland) or "positive planning" where they define the suitability of a piece of land for a specific use (i.e., where they explicitly designate sites for urban development) (see also Legally Binding Land Use Planning).

Clearly, these determinants of land consumption encourage or constrain urban development with a certain spatial logic. Some of them may explain the total pressure on the land within a region or even a nation state, but are hardly suited to identify the local hot spots of development. Examples are housing policies or mortgage schemes that support private homeownership. Other determinants can explain why certain plots of land were developed – for example, moderate land prices or above-average accessibility – while failing to explain the aggregated regional growth rate of urbanized land. Table 3 presents a set of relevant variables with their estimated explanatory capacity.

Recent studies [76, 77] have found that supply-driven factors of land consumption generally carry higher weights than the demand side. They suggest that land consumption is not only the result of demand driven by demographic and economic growth pressures or social preferences, but is also fuelled and facilitated by policies at national as well as local scales [78, 79]. For instance, the political agenda of local decision-makers in stagnating or economically declining areas often emphasizes the importance of cheap land for residential or commercial uses as a means to attract people and enterprise and thus to generate income tax. This can explain why some regions and municipalities without demographic or economic demand pressure show significant land consumption rates [80, 81]. Government policies like the commuter tax allowance in Germany, the financing of highway infrastructure in the USA, or subsidies for the development of industrial or retail development by the European Union are likely to support this effect [82].

Some scholars present evidence that the institutional fragmentation of local authorities could be another important factor explaining the rate and pattern of land consumption. According to this position, a decentralized land use governance with numerous local governments controlling urban land use is likely to promote urban sprawl as it increases the number of jurisdictions seeking for extra-budgetary revenue through land conversion to urban uses [48, 77, 83]. The size of local government units is also important in other ways – the bigger they are the less likely to be reliant on one particular investor or project, and less vulnerable to the influence of individual land owners with regard to planning policies and decisions. Furthermore, smaller communities are more likely to permit exclusionary zoning policies where local governments intend to exclude low-income groups from their municipalities [79, 84]. These policies are driven by the suburban resident's desire to protect their housing investments and to maintain their social status [83].

Landscape Planning for Minimizing Land Consumption. Table 4 Categorization of land consumption impacts

Dimension of categorization	Impact categories
Causality	Direct impacts
	Indirect or cumulative impacts
Spatial scale	Land unit-level impacts
	Context-level impacts
Issue of concern	Environmental impacts
	Economic impacts
	Social impacts
Impact pathway	Land surface related impacts
	Land use pattern related impacts
	Density related impacts
Quality	Impacts as costs
	Impacts as benefits

Impacts of Land Consumption

Systematization As mentioned above, land consumption is a by-product of demographic and economic change. In a sense, land consumption is an indicator of prosperous development since it seems unrealistic to aim for strong economic growth without any land conversion. Improvements of housing supply, the introduction of modern transport systems, or the rise of economic productivity are mostly land-consuming activities. Downs [83] points out that urban sprawl produces some benefits for metropolitan citizens. Among others, he lists low-density lifestyles and the availability of private green space, an easy access to public open spaces in the countryside, a broad choice of places to work and live, relatively short commuting times for people who both live and work in suburban areas, and the ability of citizens to exercise strong influence on local governments.

At the same time, land consumption is responsible for many undesirable effects. In the scientific literature, numerous approaches to categorize these effects have been introduced (Table 4). They refer to causality, to spatial scales of impact phenomena, specific impact pathways, issues of concern (environmental, economic, or social issues), or the quality of effects as costs or benefits.

A first useful categorization distinguishes between single, that is, direct, and cumulative, that is, indirect, impacts. Conversion of forest to residential land, for example, is a direct effect causing the loss of vegetation or the sealing of natural surfaces. However, significant land use related environmental problems such as the modification of urban climate conditions ("urban heat island") or the increase in urban runoff often result from the cumulative effects of development activities rather than single projects. They build up over a period of time and usually have more than one cause. The individual effects from a single development activity may not be significant in terms of environmental harm

Landscape Planning for Minimizing Land Consumption. Table 5 A typology of cumulative effects with some examples of land consumption (Adapted from Cooper [85, p 3])

Type	Main characteristics	Examples
Time crowding	Frequent, repetitive, and simultaneous impacts on an environmental resource	Loss of prime farmland [88]
Space crowding	High spatial density of impacts on an environmental system	Emergence of an "urban heat island" caused by the spatial concentration of artificial surfaces and a lack of green space [89]
Cross-boundary movement	Impacts occur some distance away from source	Floods affecting downstream settlements caused – among other reasons – by increases in upstream urban runoff
Compounding/ synergistic effects	Effects resulting from multiple sources or impacts that may be different in nature from the individual impacts	Drawdown of groundwater levels due to increased imperviousness and increases in withdrawal of groundwater
Triggers and thresholds	Fundamental changes in system behavior or structure	Beyond a threshold of 15% imperviousness, urban stream quality becomes poor [90]
Nibbling	Incremental or decreasing effects	Gradual loss of greenbelt land through urban development [91]

(Table 5). However, when considered with other perturbations on the same environmental component (or system), they can become significant either through additive or interactive processes [85]; see also CEQ [86] and Parr [87].

Closely related to the above-mentioned categorization, Nuissl et al. [92] differentiate a "land unit level" and a "context level" of land use impacts. Unit-level effects are the direct and immediate outcome of a change of land use on a particular plot of land. In contrast, context-level effects depend on the characteristics of the larger territory in which a land use change is taking place. The authors point out that these indirect impacts cannot be comprehended with a narrow spatial focus on the particular piece of land that is subject to a modification of land use or land cover. Examples are fragmentation effects of new roads or the attraction of motorized consumers by large-scale retail facilities.

Siedentop and Fina [45] distinguish three key dimensions of urban land use through which a broad range of land consumption impacts can be explained and modeled. These are land cover features (surface), the pattern of land use as the spatial configuration of urban and nonurban land patches, and the intensity of use (urban density). Table 6 summarizes well-documented impacts of land consumption and attributes them to certain impact pathways.

Other studies categorize impacts with respect to certain issues of concern [125–127]. Often, a reference to environmental, economic, and social effects is made. Fig. 2 outlines some frequently addressed land consumption impacts and categorizes them with regard to the issue of concern and the spatial scales of their impact in an "urban sprawl" matrix.

Review of Important Impacts First of all, land consumption has sparked environmental concerns. Environmental effects of land consumption can be primarily explained with changes of land cover features that are inevitably related to urban development [99]. Natural or seminatural surfaces are converted to urban uses with a high share of artificial, impervious surfaces and complex effects on ecological systems [90, 100, 128]. Imperviousness is defined as the sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces of the urban landscape [90, 129] (see Table 7 for an overview on the mean imperviousness of different land uses). In many studies, imperviousness has been used as an indicator to measure the

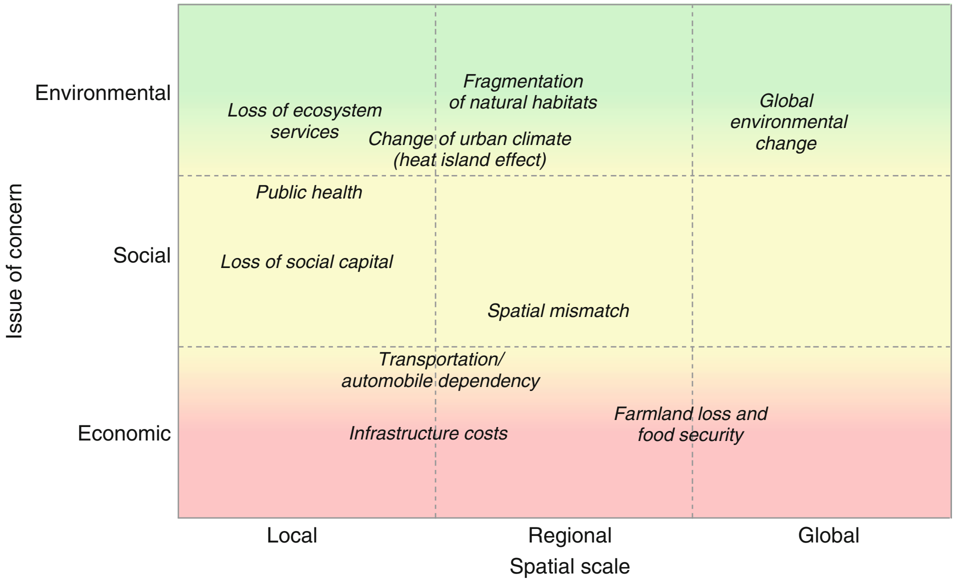
Landscape Planning for Minimizing Land Consumption. Table 6 Land consumption impacts related to distinct impact pathways (Adapted from [45])

Impact pathway	Impacts of land consumption	Sources
Change of land cover (surface)	Continuous urbanization leads to a loss or degradation of valuable open space	[88, 93–95]
	The spatial concentration of pollutants is co-responsible for high air pollution	[51]
	The spatial concentration of artificial surfaces and a lack of green space is one causative factor for the urban heat island	[89, 96–99]
	The spatial concentration of built-up land has negative effects on the provision of green space	[99]
	Urban runoff from sealed surfaces negatively affects aquatic systems (water quality, biodiversity of systems)	[90, 100]
Changes of land use patterns	Dispersed and scattered settlement patterns hold responsible for high development costs (infrastructure)	[36, 101–103]
	Dispersed and scattered settlement patterns lead to higher travel distances and thus higher climate gas emissions	[62, 104–106]
	A discontinuous urban growth brings about higher levels of habitat fragmentation	[107, 108]
	The over-concentration of population and monocentric urban systems have a risk of higher levels of traffic congestion	[109, 110]
Change of urban densities	Low residential densities come along with a high level of automobile dependence	[111, 112]
	Low residential densities are usually associated with higher travel distances	[11, 49, 113–115]
	Low residential densities lead to less cost-efficient and effective public transit	[116–118]
	Low residential densities result in higher per-capita development costs (urban services)	[36, 103, 119]
	Low residential densities lead to higher energy use for housing (heating)	[120, 121]
	Low residential densities are co-responsible for negative health effects (due to physical activity levels)	[14, 122–124]

impacts of land development on terrestrial and aquatic ecosystems. Imperviousness physically limits the infiltration of rainfall into the ground. Rainfall and snowmelt water disabled to infiltrate becomes surface runoff. Studies have shown that the urban runoff can be more than twice as high in urbanized than in rural areas with more natural land cover features [130]. Thus, soil sealing in highly urbanized areas is widely viewed as an important causative factor of flood risks [75]. Due to the fact that urban runoff water carries with it chemical pollutants (e.g., from automobile traffic or industrial land uses) imperviousness also contributes to the biochemical degradation of aquatic ecosystems. Based on many empirical studies, Moglen and Kim [128] estimate that when the rate of paved surfaces exceeds a threshold of 10–15% various indicators of biological stream quality decline markedly.

Moreover, the high percentage of imperviousness is also co-responsible for highly modified meso-climatic conditions in large urbanized areas ("urban heat island"). The spatial concentration of artificial materials with specific thermal characteristics creates local temperature anomalies leading to a higher average temperature in the dense urban fabric as compared to the urban periphery [89, 96, 97].

In addition to the magnitude of land conversion and imperviousness, the characteristics of the land that became urbanized within a specific period of time have



Landscape Planning for Minimizing Land Consumption. Figure 2
The impact matrix of land consumption

Landscape Planning for Minimizing Land Consumption. Table 7 Percentages of imperviousness for different categories of urban land use (Adapted from [92, 128, 131, 132])

Land use category	[131]	[92]	[132]	[128]
	Imperviousness (in percent)			
Residential	35–65	40–80	49	25–65
Mixed use	65	–	44	–
Public open spaces	–	–	15	–
Commercial and business	80	–	–	85
Institutional (public use)	–	–	59	50
Industrial	76–80	80–100	64	72
Transportation	58–63	80–100 (roads) 20–40 (rail)	–	75
Urban recreation (sport fields, public parks, private gardens)	4–8	–	–	–
Agriculture	0	–	2	–
Forest	–	–	2	–

to be taken into account (e.g., soil quality, habitat quality, vegetation, etc.). Of particular concern is the loss of prime agricultural land due to its importance for the long-term competitiveness and sustainability of agriculture [94]. The European Environment Agency [40, p 176] estimates that the "continent's best soils" are sealed due to the fact that most urban centers were built on fertile valley soils and around estuaries (see also [88, 133]). Hasse and Lathrop [94] present quantitative findings that prime farmland is more vulnerable to urbanization than farmland of lesser quality. Urban development in more and more fragmented agricultural landscapes can also be problematic for the production of food and fiber on the remaining farmland. For instance, conflicts between farmers and their residential neighbors "can arise over noise, chemical applications, and smells that are part of farming" [134, p 2].

In addition, dispersed and fragmented land use patterns are a crucial contributor to landscape fragmentation, which is characterized by a process of perforation, dissection, and isolation of habitat areas and natural or seminatural ecosystems [107]. Many scholars regard fragmentation as a major cause of the alarming loss of species all over the world [108, 135].

The (not purely monetary) costs for providing settlements with public services are commonly addressed in urban sprawl studies that focus on the economic effects of land consumption. In 1974, the "costs of sprawl" study [136] presented empirical evidence for a negative interdependency between the density of residential developments and the fiscal costs for providing basic urban services. The findings of this study triggered an intensive dispute not only with respect to the implications for urban development policies but also in terms of methodological uncertainties. A couple of subsequent studies confirmed the results of the 1974 work (see [36] with many references); others disputed the relevance of urban form variables on infrastructure costs [137, 138]. As a bottom line it can be said that it is widely acknowledged today that low-density and dispersed urban developments are more cost-intensive than more compact development patterns (see also [101, 139–141]).

The impact of land consumption on motorized transport demand is probably the most frequently discussed issue in this field of research. Many scholars have shown that spatially dispersed urban areas accompanied by low densities contribute to larger travel distances [104, 114, 142, 143]. Based on a meta-analysis of the relevant literature, Ewing and Cervero [113] come to the conclusion that single variables of urban form have a relatively minor effect on motorized transport demand. However, the combined effect of several urban form variables on travel can be significant (see also [144]). Next to urban density, the accessibility of workplaces and other destinations, the mix of different land uses, the availability of public transit and urban design features are regarded as being influential on transport. Some critics dispute the causality between urban form and travel behavior, pointing to the possibility that private households self-select themselves to places that are in accordance with their preferences for particular transportation modes [145]. At the same time, studies that controlled for demographic, socioeconomic, and attitudinal variables (such as household income, family size, or age) presented contrasting results that identify a significant effect of urban form on transport [143, 146, 147]. Everything else being equal, households in peripheral low-density environments have longer travel distances and tend to travel by car more often than their inner-city counterparts.

Lastly, land consumption and urban sprawl have also been criticized for unintended social outcomes (e.g., [148]). The "spatial mismatch" debate, starting in the 1960s (see [149] and [150]), addressed the extent of limitations on residential choice for minority populations (especially Afro-Americans in the USA), combined with the intra-regional decentralization of employment. Proponents of the spatial mismatch hypothesis argue that the exclusion of low-income and nonwhite households from suburban communities together with the continuous spatial dispersal of jobs especially for low-skilled employees is responsible for the high rates of unemployment and low earnings of minority population members living in central cities. More recently, studies found evidence that low job accessibility in public transport catchments negatively affects the employment probability of social groups with a poor availability of cars [151].

The very recent debate concerning the effects of urban sprawl on public health – with a special focus on the relationship between urban form variables and physical activities with their corresponding health implications – demonstrates that the discussion on land consumption impacts is not closed (e.g., [14, 122, 124]). Moreover, the verification of alleged impact hypotheses with credible and disaggregated data and more robust methodological designs will help policy makers in justifying their potentially restrictive policies and measures.

The Means of Spatial Planning to Minimize Land Consumption

The Aim of Spatial Planning

The desire to control the dynamics of land consumption was one of the earliest motivations for spatial planning. However, while this desire used to be of minor importance in comparison to the goal of mitigating land use conflicts and safeguarding the most rational possible form of urban growth, it has become one of the major issues in land use policy only more recently (e.g., [152]). This issue is probably most disputed in the USA where public concern about sprawl grew heavily in the recent past [153], resulting in a strong anti-sprawl movement that meets strong opposition by more liberal academics and planners who emphasize the importance of individual choice and the free market (e.g., [28, 93, 154–156]). However, elsewhere, most notably in Western and Central Europe and Australia, this debate has also gained considerable momentum (e.g., [55, 157]).

As has been shown in the previous part of this contribution, at least in sustainability science and environmental politics it is now widely acknowledged that sprawl causes ecological damage, increases the need to travel, makes service provision more expensive, and has additional social and economic impacts. In 1999 the European Spatial Development Perspective recommended that "member States and regional authorities should pursue the concept of the 'compact city' (the city of short distances) in order to have better control over further expansion of the cities." "For this purpose," the document continues "co-operation between the city and the surrounding countryside must be intensified and new forms of reconciling interests on a partnership basis must be found" [158 para 84]. This quotation gives a typical example of the risen sensitivity of the land consumption issue. However, while it implies a strong quest for the minimization of land consumption the quotation's latter part hints at the general aim of spatial planning to provide a legal and conceptual framework that facilitates societal progress and economic growth. Insofar, it is a major challenge for spatial planning to balance the minimization of land consumption with other planning goals that are associated with development. To achieve this complex mission, spatial planning has quite some strategies and instruments at hand, many of which are well proven.

A Taxonomy of Planning Instruments

Basically, spatial planning is about the organization and regulation of land uses. Thus, almost all strategic and instrumental approaches developed by spatial planning are potentially apt to contribute to the minimization of land consumption – provided they are used to pursue precisely this goal.

The debate on potential policy responses to land consumption is rather broad and a great variety of policy strategies has actually been put in place across different countries so as to mitigate land consumption. Therefore, first of all a broad categorization of planning instruments seems to be helpful, which groups these instruments according to the general approach they use. A common way to achieve such classification is to divide public policies into those concerned either with (a) regulation, (b) spending, taxation, and subsidy, or (c) advocacy. Considering the phenomenon of urban sprawl in the USA, Bengston et al. [159] employed a similar three-part classification of policy types for the control of urban sprawl. Adopting and slightly modifying their approach, we propose to differentiate the means of spatial planning to minimize land consumption according to where they are located on the continuum that expands between the poles of two basic planning principles:

- *Planning*, reflecting the "traditional" regulatory approach of spatial planning to set legally binding rules for the use of land via regulative plans, and
- *Market*, reflecting the "economic" approach of land use policy that employs "market-based instruments" that modify incentives in a way that leads actors to use the land in the intended manner. For instance, taxation schemes that put an additional cost on the development of land are surely among the most efficient means to minimize the total amount of urbanized land (e.g., [160]).

Between these two poles (somewhere "halfway") one can discern an array of instruments, which are primarily managerial by character and that basically aim at impacting on the decision-making processes that eventually lead to regulative or market-oriented land use policy measures. This group of instruments can be attributed to a third planning principle:

Landscape Planning for Minimizing Land Consumption. Table 8 A taxonomy of land use policy instruments

Governance principle	Planning approach	Examples of strategies and instruments
Planning	Regulation (law)	Land use planning, that is, Zoning, for example, [162, 163]
		Urban design planning (e.g., density controls), for example, [164, 165]
		Transit planning [166, 167] etc.
Management	Persuasion (information and communication)	Forums and roundtables, for example, [168, 169]
		Information campaigns, for example, [170, 171]
		Land use change assessment and forecasting tools, for example, [172, 173] etc.
Market	Modification of incentives	Development taxes, for example, [174, 175]
		Subsides (e.g., urban regeneration), for example, [176, 177]
		Tradable permit schemes, for example, [161, 178] etc.

- *Management*, reflecting the "persuasive" approach that tries to change the behavior of land using actors, either by providing them with information on the consequences of their behavior or by involving them in a communicative process together with actors that want to restrict land consumption.

These planning principles are of course ideal types. In reality policy responses and planning instruments that address the problem of land consumption are frequently combinations of several instruments that entail different principles.

Table 8 illustrates the three general approaches land use policy can adopt to pursue its goals, including the goal of minimizing land consumption. However, only the regulative and the persuasive approach fall into the scope of spatial planning in a strict sense, while the modification of incentives is usually to be achieved in other policy fields, for instance taxation or social policy [161]. In the following sections, we shall therefore highlight those spatial planning instruments that can be attributed to either the regulative or the persuasive approach while economic instruments do not fall into the scope of this contribution. (However, this must not be misunderstood as a neglect of the latter's indisputable effectiveness.)

Regulation

Sector-Specific Planning and Comprehensive Land Use Planning In virtually all countries there are different fields of public policy, legislature, and planning that define regulations as to the use of land. Frequently we find a differentiation between comprehensive land use planning on the one hand – as a policy field that is focused on resolving land use conflicts and safeguarding the rational use of land – and sector-specific fields of policy making and planning on the other hand. They both produce legal framework conditions on how a piece of land may be used, but the latter formulate only particularistic demands for land (e.g., by defining the location of technical infrastructure, water reserve zones, or nature preservation areas) and leave the task of coordinating these demands and interests to land use planning.

In principle, all kinds of public planning that have an impact on land use can contribute to achieving minimal land consumption. For instance, when planning a new power plant or road infrastructure it is always possible and worthwhile to consider how much land needs to be developed to realize the project. The field of environmental policy is particularly important as to sector-specific plans with the potential to minimize land consumption. The plans that are elaborated within this policy field, frequently labeled landscape planning, are usually restricted to defining nonurban areas that must not be developed in the future and include more or less detailed rules on how these areas ought to be used. However, the kind of planning that is most relevant with regard to land consumption and its minimization is almost always comprehensive land use planning.

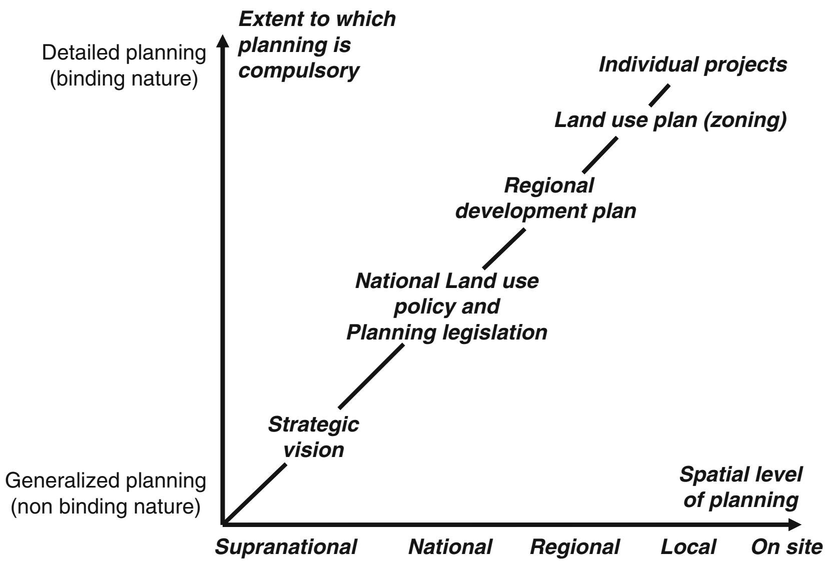
Land use planning is an integrative endeavor. Its major task is the coordination and balancing of the different demands for land, which are put forward by industry and commerce, by private households, or, not least, by sector-specific policies, that is, authorities who are in charge for the provision of the public with infrastructure and services. The ability of land use planning to achieve this integrative task, and thus to prevent the formulation of contradictory public demands or rules regarding the use of land, varies between different countries and largely depends on the functionality and powers of the respective system of land use planning (e.g., [179]). However, even in countries with well-established (and more or less sophisticated) systems of comprehensive land use planning it is often the case that sector-specific plans drawn up by different authorities prove inconsistent.

Legally Binding Land Use Planning Virtually everywhere, land use planning builds on the principle of *distinguishing different kinds of land use*. This principle, and the related practice, is usually named "zoning" in the English-speaking world. Zoning basically implies the delineation of particular (non-overlapping) pieces of land for which acceptable and unacceptable kinds of land use are defined more or less precisely. This may include the definition of the kinds of activities that will be tolerable on a particular lot (such as open space, residential, commercial, etc.), or the regulation of building height, lot coverage, obligatory shares of green space, and similar characteristics, or some combination of these. The primary purpose of zoning is to segregate uses that are deemed incompatible.

The most basic distinction that can be made via zoning is between urban land, including land that is dedicated to future development, and nonurban land. Thus, the principal instrument of regulative land use planning to minimize land consumption consists in the preparation and legal enforcement of land use and development plans, which, by distinguishing between these two land types, confine urban development to a limited area and usually include regulations regarding the character and intensity of urban land use.

Depending on a country's planning legislation, land use planning either formulates rules only for the urban area of a respective administrative unit, including the demarcation of this area that may contain yet undeveloped greenfield land, or it defines land use classes (zones) for an entire administrative territory, which likewise includes the *classification of developable land*. Usually land use planning, like many other forms of public policy, operates at different spatial scales – thus yielding regulatory efforts at the local, regional, national, or even supranational level, which mainly differ as to both the precision and the enforceability of directives (see Fig. 3). This constitutes a *hierarchy of plans*, with the plans on the upper levels specifying the framework conditions the more detailed local plans must meet. At the same time, however, it is a basic principle of regulatory land use planning that the more general "upper-level" plans must not be at odds with existing local (zoning) plans. In the hierarchy of land use planning it is usually only the local plans that enforce the containment of urban development by categorizing the different pieces of land in a way that is legally binding for land owners and investors.

Beyond the fact that most countries in the world have a system of land use planning, which, in one way or other, yields compulsory plans that prescribe how the land may be used, this planning system can be organized rather differently. Accordingly, there is an immense diversity of forms that regulatory land use plans can take in terms of legal foundation, regulatory power, planning symbols, relation between planning tiers, or content – ranging from plans that endeavor to grasp and regulate the full complexity of spatial development on the one hand to elementary zoning plans that include only a few basic predictions as to the permissible developments on the other. In many European countries, for instance, local plans are framed by plans prepared at the regional level, that is, by medium tiers of administration. Where such an intermediate level of spatial planning is lacking there is sometimes a distinctive antagonism between the national state and the communes. In addition to the comprehensive land use plans, in some countries, such as the Netherlands or Germany, detailed urban design plans, specifying the physical form of future development, are prepared, especially for areas where some new development is to be expected. Other countries, such as the UK, rely mainly on the comprehensive land use



Landscape Planning for Minimizing Land Consumption. Figure 3
Stylized correlation between spatial level of planning and precision as well as enforceability of planning (Source: [180] modified)

plans and supplementary policy to control development, without the preparation of detailed urban design plans.

The use of compulsory land use planning can be based on two fundamentally different ideas. On the one hand, land use plans may be drawn up to provide for the legal preparation of future development by defining the location of developments or facilities that are to be realized in future – this can be called "positive planning." On the other hand, land use plans are frequently necessary to steer and curtail urban growth as well as to prevent certain unwelcome developments by excluding particular uses for particular lots – this can be called "negative planning ."

From its beginning in the nineteenth century modern land use planning was basically devised as a response to the rapid outward expansion of urban areas in the course of industrialization. Initially, planning thus adopted the "positive" rather than the "negative" approach in that it was not primarily concerned with the containment of urban development and land consumption but rather with its preparation and coordination. The idea that land is a finite resource emerged only much later, in recent times. It is also important to note that an effective system of land use planning that draws on the principle of zoning did not emerge simultaneously throughout the world. Rather, in contrast to those countries in western, northern, and central Europe where the idea of urban and town planning is well established and accepted, the current planning legislation and planning practice is a fairly recent phenomenon in many countries and, in even more countries, remains a highly contested area of policy and a somewhat toothless tiger.

The "negative" approach toward land use planning is clearly most effective when it comes to curtailing land consumption. At the same time, however, it usually means a considerable limitation of the landowners' discretionary scope regarding the use of their sites. It is therefore also particularly prone to provoke sharp resistance in particular at the local level where it is often in conflict with the interests of land owners, investors, and politicians (e.g., [181]). Hence, it is often recommendable to combine "negative" and "positive" planning regulations as the latter are usually less contested and can help making urban development less land consuming, too. An example for such combination is the permission to develop the land that is dedicated to urban uses at a considerable density (thereby lessening the pressure on greenfield land) while at the same time marking out extensive areas where building activities are strictly prohibited.

Regulatory Planning Instruments Beyond Legally Binding Land Use Planning In addition to its traditional instrument, compulsory land use plans, regulatory land use planning has a wide range of other means at hand that can be used to minimize land consumption either directly or indirectly. Four more recent examples of these additional regulatory means that have earned much attention in contemporary land use policy debates will be sketched out in the following. All of them are inspired by the normative ideas of environmental conservation and sustainability. While one of these instruments aims at influencing land use patterns directly, the other three do so in an indirect fashion.

1. In many countries planning legislation enables authorities to define *minimum lot sizes* or *minimum building density*. Both can be employed in order to prevent land consumption and urban sprawl (e.g., [182]). Minimum lot sizing is usually meant to preserve the rural character of the landscape by prescribing a size of plots that exceeds the usual size of residential sites by far. However, as an attempt to save the rural character of an area minimum lot sizing can easily fail, in particular in the vicinity of urban agglomerations, when affluent households start acquiring the rural plots in order to build their house there (e.g., [183]). The definition of minimum building density, on the other hand, prescribes an economic use of urbanized plots that does not "waste" land. Involving a rather far-reaching and detailed regulation as to the usability of a certain plot of land, this instrument is most feasible in a spatial context where there already exists a high-density building structure and a political context where the power of spatial planning is generally accepted.
2. The proposal to coordinate the development of land through *tradable permit schemes* combines regulative land use planning with economic principles. In the USA, there are already several examples where this idea has been implemented [178, 184] but its intense discussion has also progressed in other countries such as Germany [185] or Italy [186]. Tradable permit schemes usually involve "a cap-and-trade" approach, which works as follows: State authorities define the maximum amount of developable land and then issue a limited number of permits that allow developing a certain share of this total amount of potentially new urban land. After their assignment to the actors, either authorities or private landowners, who – according to a respective country's legal system – are entitled to use them in order to develop land, these permits can be traded among the actors. Where the demand for building land exceeds the initial assignment of permits, additional allowances can be requested. In turn, actors with a weak demand for building land can put their surplus permits on offer. The basic hypothesis underlying the idea of tradable permit schemes is that the trading of allowances will eventually lead to the most efficient land use pattern (because local planning entities, developers, or property owners are deemed rational actors who compare the expected profitability of new building land to the market price for the required permits). However, the introduction of tradable permit schemes may also entail some difficulties. First of all, it is open to debate how the "cap" should be defined and how the initial allocation of permits should be organized (e.g., via auctioning or via a fair distribution between actors free of charge) without distorting the balance between actors and without jeopardizing institutional rights of local communes or property owners. From an environmental point of view one might also object that the system is only focused on aggregate land consumption figures and neglects the different environmental values and public good functions of different plots of land (e.g., [187, 188]). Yet again, a "cap-and-trade" scheme of tradable permits appears to be a promising instrument for minimizing land consumption as it provides the land-consuming actors with the highest possible decision autonomy, while at the same time assuring the achievement of the cap previously set.
3. In many countries, the rising awareness for environmental issues has led to the introduction of laws and schemes that provide for the *compensation of ecological infringements* by new developments. These are based on the simple principle to ask anyone who is responsible for an investment with negative environmental impact to invest into the improvement of ecological conditions elsewhere.

In several countries a system of compensation has developed in recent years, including, among others, pools of plots where compensation measures may be implemented (by improving the ecological value of a respective plot) as well as detailed evaluation schemes that allow quantifying both the environmental impact of a particular development as well as the environmental benefit of compensation measures [189]. Compensation systems of this kind can help minimize land consumption in at least two respects. On the one hand, they simply make the development of new land more expensive, thereby impeding investments that foster land consumption. On the other hand, activities that mitigate previous land consumption can be acknowledged as compensation measures for new developments. Insofar it is for instance possible to oblige land developers to dismantle the water-bound surface of a brownfield plot or tear down empty premises.

4. The *definition of rules concerning the process of land use planning* can be an important control ensuring the efficient use of existing or planned urban areas and infrastructure, avoiding unnecessary land consumption. The obligation to check public plans for their eco-friendliness, including their impact in terms of land consumption, which is required by a directive of the European Union (SEA Directive 2001/42/EC) since 2004 is a good example. The SEA procedures obligate land use planners and decision-makers to systematically evaluate the likely effects of a plan on the environment and to propose reasonable alternatives of the proposed plan or program. Therefore, the SEA can stimulate planners to look for less land-consuming ways to reach their goals. Another example is the "sequential test" in British land use planning. It requires local authorities to seek suitable brownfield areas first before preparing greenfield land. In the beginning this the "sequential test " only applied to new retail or leisure development [190], but more recently the concept has been extended to planning for residential development, thereby giving priority to reusing previously developed land within urban areas, bringing empty homes back into use and converting existing buildings in preference to the development of greenfield sites. This strategy is particularly relevant with respect to those regions where land consumption occurs in combination with decline (see the contribution by Haase in this volume).

Persuasion – Indicative and Informal Means of Land Use Planning

Besides the "hard" instruments of regulatory land use planning spatial planning has a wide array of "soft" instruments at its disposal. Even though it is the defining characteristic of these instruments that they do not involve the definition of legally binding rules for the use of land, they can nevertheless be very effective when it comes to minimizing land consumption. They include rather different tools such as nonbinding development and actions plans [191] (more or less sophisticated concepts for the organization of), round-table discussions, workshops, and public forums (e.g., [192]); GIS-based decision support systems (e.g., [193]); or initiatives to promote an urban rather than a suburban lifestyle [170]. Generally speaking, these "persuasive" planning instruments attempt to create a commitment to a common goal (i.e., to the goal of minimizing land consumption) and to find cooperative solutions for problems arising from conflicting demands on land use (whereas the regulatory instruments seek to solve these problems by exertion). Reflecting the experience that traditional "blue-print-planning " that mainly draws on regulatory planning tools is often unable to achieve its goals – due to its inability to handle the complexity of societal production of urban space [194, 195] – "persuasive" instruments are broadly accepted today and advocated as an alternative means of progressing in spatial planning.

It hardly comes as a surprise that indicative and informal instruments of spatial planning work fairly well in situations that entail a win-win-structure – for instance, if the national government has decided to allocate a big infrastructure investment in a particular region and the municipalities in the region have to discuss and agree about the details of the project. On the other hand, if a "zero-sum-game" is to be played it is much more difficult to convince the officials in charge to engage in some kind of cooperative action. This becomes manifest, for example, with most attempts to persuade, or push, municipalities to transfer some of their formal competences in spatial planning to the regional level, for example, a new supra-local authority that is installed to organize land development in an urban agglomeration [196].

The provision of information for those actors whose decisions actually determine the pattern of spatial development is a very "soft" but also, at least sometimes, a very promising strategy of spatial planning . With regard to the public actors the monitoring of spatial development and land use change has long been discussed as a means to promote sustainable development (e.g., [197]). The focal point of this discussion is the assumption that an enhanced knowledge on the environmental and social drawbacks of land consumption may lead policy makers to the conclusion that they should call for more efficient forms of spatial development. Moreover, such knowledge can serve as an additional source of legitimacy for the efforts of public authorities (at the supra-local, i.e., regional or national, level) that strive for a containment of land consumption and urban sprawl. Accordingly, various kinds of planning information systems have been designed the main task of which is the continuous provision of information on land use change to decision-makers, and sometimes also the public (e.g., [38, 198]). In addition, there is a further group of instruments that not only aim at monitoring the process of land use change but also the effectiveness and success of growth management policies altogether (e.g., 75, 199, 200).

Apart from providing decision support to professionals, the publication of data from land use monitoring systems also helps raising public awareness for land consumption and facilitates participation in the planning process. While much of the decision-making surrounding land use changes can be attributed to the calculation of economic costs and benefits by individual firms and households with little concern for wider socio-environmental matters, it is interesting to speculate on the extent to which behavior might be changed through "promoting a non-sprawl culture (. . .) through education and dissemination" and by "advertising and marketing techniques" [201, p 19], similar to previous campaigns, for example, in support of waste recovery or against smoking in public places.

Models and Paradigms of Urban Development

Whether or not the goal to minimize land consumption can be achieved is not only dependent on the availability of appropriate strategies and instruments to influence or regulate land use changes. Rather, a normative idea on the optimal spatial structure of urban areas that provides orientation in applying these instruments is likewise important. Spatial planning has developed a number of models and paradigms of urban development which, among others, make a strong claim for an economic use of land. As regards the minimization of land consumption, (1) the Green Belt and the Urban Growth Boundary, (2) the various leitmotifs of urban development that promote the compact, polycentric, and mixed-used city, (3) and the prioritization of urban regeneration are among the most important of these normative ideas. Although addressing the complexity of the urban system at rather different levels, these ideas can be seen as specific kinds of planning instruments in that they all entail concrete assertions on how the result of land use change, that is, spatial planning, should look like. They are planning instruments in their own right, but both of a more "substantial" (i.e., material) nature than the instruments discussed above (which are neutral in terms of content and can be used to pursue very different goals). To unfold their instrumental character in the planning process, however, models and paradigms of urban development usually need to be sustained by employing both regulative and persuasive instruments (i.e., the more "instrumental" planning instruments) to implement them.

1. The delineation of *Green Belts* or *Urban Growth Boundaries*, respectively, are among the most famous "tools" designed by spatial planning so as to provide a clear orientation about where to steer new development to and where to prevent urbanization (e.g., [202–204]). While both involve the idea to define a ring of open land that surrounds the urban area, the former notion usually implies a precisely defined line beyond which no building activity must take place whereas the latter is the more generic notion that is often used in nonbinding, regional plans and thus needs to be enforced by specific plans that prohibit development in the Green Belt areas. As long ago as 1944 Abercrombie's Plan for Greater London successfully employed the idea of a green ring that separates the metropolis from the surrounding

landscapes – combined with the designation of a series of "new towns" as decentralized growth centers [205, 206]. In particular the concept of the Urban Growth Boundary is difficult to apply in densely populated regions where a sharp distinction between urban and rural areas is often hardly possible. In addition, there is a broad debate in the USA on whether the definition of a rigid boundary around a settlement is indeed the most effective means to curb urban sprawl and its associated negative impacts (e.g., [207]). Several scholars claim to have proven this assumption (e.g., [208]) whereas others doubt it (e.g., [209]). Likewise, Green Belt policies or Urban Growth Boundaries can prove unsuitable in a situation where informal housing is a frequent phenomenon [210]. In such a situation it is hardly possible to limit the outward expansion of the urban area, while, at the same time, it is important to involve the inhabitants of the proliferating informal areas in the planning process, rather than posing threats to their security of tenure by a desk-top zoning of land uses [211]. The implementation of Green Belts and Urban Growth Boundaries requires the decided use of compulsory land use plans in the way of "negative" planning. It will only be successful if there is broad support for a policy that deprives land owners of the chance to develop their sites if this site is located beyond the imaginary line planners have conceived between the urban and open space [212]. Therefore, whether or not a Green Belt or an Urban Growth Boundary can be implemented in practice largely depends on the distribution of political powers between the main actors of urban development, and in particular on the power of regional planning to pursue its goals.

2. Spatial planning has ever since been strongly influenced by the predominant *leitmotifs and guiding stars* of the time regarding the optimal urban environment – in fact without its foundation in visionary ideas planning would be a somewhat uninspired, bland business. Today the chief guiding stars in urban planning promote, in one way or another, the economic use of land and thus the minimization of land consumption. This is particularly true of the ideal of the mixed use and compact city (e.g., [213]), which is at the heart of, for example, the New Urbanism campaign in the USA [214] as well as the discourse on the European City that has become influential in particular in Central Europe [215]. These guiding stars have developed over the last several decades as a reaction to the neglect of the particular qualities of "urban" environments that was characteristic of the postwar principles and trends of urban development [216]. Decentralized concentration is another leitmotif of spatial development that rather addresses the regional level of planning. It is based on the somewhat dialectic idea that, on the one hand, development (including the development of fresh land) should be promoted in less privileged, peripheral regions but, on the other hand, should be steered to selected locations in order to prevent an inefficient and unwelcome dispersion of development activities [217, 218]. Although the leitmotifs and guiding stars of urban planning are usually not primarily focused on land use issues but rather sketch out a more general idea of "the urban" (which is embedded in an even broader utopian idea of society), their clear intention to concentrate on urban development can mean considerable ideological support for a policy in favor of minimization of land consumption.
3. It is widely acknowledged that policies to minimize land consumption will only be successful if they go hand in hand with efforts to encourage *urban regeneration*, that is, the revalorization or reuse of land that has already been developed [219, 220]. Within the last around 50 years, in many countries a variety of strategies and instruments have emerged to promote urban regeneration. These include specific legislative measures that regulate urban renewal processes (e.g., [176]), urban regeneration schemes aiming to reestablish the attractiveness of inner urban areas (e.g., [221]), congestion charges in inner urban areas [222], or graduated density zoning [223]. These efforts help making the existing urban area as attractive as the newly developed areas as a place in which to invest, develop, produce, live, and work, from the perspectives of economic return, social satisfaction, and environmental quality [224]. If the endeavors to promote urban regeneration are successful they provide a powerful support for the minimization of land consumption;

if they fail it will be hardly possible to (re-) direct the focus of investors and households away from suburban Greenfield land and to win them over for more compact development patterns.

Practical Challenges: Spatial Planning as a Governance Endeavor

There is no doubt that spatial planning in most countries in principle disposes of the means to minimize land consumption. Accordingly, we can find countless examples where decided planning efforts have contained land consumption (e.g., [20, 225]) as well as several studies that conducted a comparative evaluation of growth management policies in different regions and found them to have significant impact (e.g., [226–228]). On the other hand, some authors remain somewhat skeptical as to the effectiveness of growth management via spatial planning (e.g., [79, 229]) or even oppose the very idea of intervention in the dynamics of land use change (e.g., [155, 230]). When it comes to discussing whether the actual containment of land consumption has indeed mitigated the negative impacts attributed to urban sprawl, opinions are even more split as can be seen from countless studies on the urban sprawl issue (see [219, 231, 232], to name but three examples). To give an example from the USA for this divergence of expert views: When comparing federal states with and without growth management programs, Nelson [21] and Kline [233] arrive at completely contrary conclusions as to the success of these programs.

However, the mixed opinions about the overall success of efforts to reduce land consumption by means of spatial planning are only one important aspect. It is likewise essential to account for the fact that the implementation of such efforts is by no means only dependent on whether planners or other experts expect them to be successful. Rather, spatial planning is the result of a political process (and not just a directive endeavor possibly led by public representatives who are highly conscious of environmental issues) [77]. In other words, the mere existence of powerful planning tools that can restrict land consumption does not guarantee their use. Frequently, the problem is not the availability of legal controls but their usage by different public agencies who by no means always regard the minimization of land consumption a top priority (e.g., [234]). Furthermore, minimizing land consumption is a common interest goal that has to be pursued mainly by state authorities (supported by environmental groups) against both other common interest goals (like increasing the number of jobs or the local tax base) as well as the individual interest of land owners and developers to use the land for their purposes (e.g., [235]). Thus, the question arises whether some provision can be made that spatial planning works in favor of a minimization of land consumption at all.

Due to the differences that exist between the planning systems of different countries – and also because of different legal and administrative cultures (e.g., [236]) – it would not be feasible to provide general recommendations as to how spatial planning systems can be instigated to minimize land consumption. Neither is it possible to formulate universally applicable assumptions as to the optimal strategy of land use policy and spatial planning, let alone the use of particular planning instruments. Rather, "anti-sprawl policies must be tailored for the particular patterns extant in the area at hand" [237]. However, it is possible to name a few aspects that should be taken into account wherever spatial planning is expected to help minimizing land consumption.

As we have seen, different state tiers usually have their own means of land use planning that they employ to pursue their specific goals. As a rule, it is at the local level where the opportunity to curtail land-consuming development is usually most, but the willingness to actually inhibit development least pronounced [238] – while we often find the reverse situation at the regional or national level. The task of minimizing land consumption is therefore a characteristic problem of multilevel-governance. This is particularly so where local authorities largely depend on their own tax bases (like in the USA or Germany) because this situation tempts them to use their power to dedicate the land to certain uses to attract tax payers or investments (e.g., [239]). Administrative fragmentation can further aggravate this situation as it increases the number of competitors trying to attract investments by offering fresh land (e.g., [240]; see also Drivers of Land Consumption). Overall, it is important to note that planning law provides local authorities with both the means to minimize or to promote land consumption – and they will often use it to promote growth rather than contain development.

As the containment of urban sprawl and the preservation of the landscape is often an important goal of supra-local land use policies, regional planning can play a key role in controlling land consumption. It can impose a set of aims and provide a framework for the operation of planning on lower government tiers. It can also organize a process in which different actors, including the region's local authorities, develop a joint idea on the future spatial structure and land use patterns of the region [241]. The commitment of local authorities and other actors to such idea will usually be the stronger the tighter they were integrated in the process of designing the common plan, beyond the usual consultations. Generally speaking, it is advisable to enact growth management policies at a spatial scale that is sufficiently large to rein in local parochialism ([31, 226]). With respect to the situation in the USA, Bengston et al. suggest that "with regard to vertical coordination (...) growth management is most effective within a statewide context, so that each level of government coordinates their plan with other governmental levels. Horizontal coordination is needed to help avoid situations in which growth management policies in one jurisdiction undermine policies or create burdens in neighboring communities" [159].

However, it may well be the case that regional or state authorities are hardly inclined to enact a containment of land consumption because they too sometimes emphasize growth as a major aim of public policy. This situation is particularly likely to occur where the responsibility for regional planning lies with an association formed by the region's local authorities (as is the case in many federal states in Germany). Razin [242] has questioned the likelihood of land consumption being successfully controlled by "macro-scale regional plans" and planning regulations and argues in favor of changes to both local tax regimes and local government structures as a more effective approach.

It can be concluded that spatial planning alone will hardly suffice to minimize land consumption. Therefore it should be complemented by other means of public policy (e.g., [19]). In particular three aspects are worthwhile considering in this respect:

1. Firstly it is important to consider the potential land-consuming effects of all types of public policy, for instance, land readjustment policies (e.g., [243]), tax policies (e.g., [244]), subsidies (e.g., [245]), and, in particular, public investments in transportation infrastructures(highways, public transport, parking lots, etc.). There is considerable evidence that the latter stimulate urban sprawl [246, 247]. For instance, radial rapid transit systems in urban agglomerations, together with park and ride facilities, do not only define the potential nodes of compact development but usually also enhance the attractiveness of suburban locations (as compared to the inner city) by improving their accessibility and making the journey from suburbia to the urban core more convenient.
2. Secondly, economic policy instruments can significantly support spatial planning in its attempt to minimize land consumption [187]. These instruments can be used to profoundly alter the framework conditions for individual action and thus to make "land-consuming activities" much less attractive [248]. In this vein, a number of suggestions are available on how fiscal incentives may be introduced that work in favor of the minimization of land consumption [175]. Likewise, the aforementioned tradable permit schemes provide an example of how regulatory land use planning may be combined with economic instruments.
3. Thirdly, it seems obvious that a policy that really aims at minimizing land consumption has to be much more decisive in supporting inner-city (in comparison to suburban) developments than is the case today [249, 250]. In particular, this could mean that subsidies and tax-depreciations for greenfield developments must be abolished, or even allowed only for inner urban projects.

Future Directions

It is widely accepted that extensive land consumption leads to the unwelcome loss of open land and natural resources, causes ecological damage, generates unnecessary traffic, wastes energy, leads to atmospheric pollution, and imposes economic costs on local authorities as inner urban services and amenities lie underused – let alone the potential social effects of urban sprawl such as the exacerbation of spatial social segregation and the exclusion of non-car-owning households from a good deal of work and leisure facilities. The minimization of land consumption is therefore usually an important goal of land use policy. Spatial planning is the major means to pursue and achieve this goal although the heydays of spatial planning and regulation of land use have been in the 1960s and 1970s and are long over. Looking to the future, however, we may expect spatial planning to increase in importance again, mainly because of the risen concern about environmental issues and the introduction in many countries of stronger requirements for considering the environmental impact of development.

Overall, there exists a wide range of strategies and instruments that can be employed by spatial planning to bring land consumption under control. The strategies and instruments that are in use in different countries share many basic features – however different they may be in detail, in particular due to the peculiarities of the respective legal system. Against this background, it will be a crucial task for future applied research on land use and spatial planning to continue with the ongoing efforts to evaluate the various instruments and strategies that aim at minimizing land consumption (which were mentioned above in particular in Practical Challenges: Spatial Planning as a Governance Endeavor). Apart from this general assertion, regarding the utilization of planning strategies and instruments a series of relevant issues and research questions can be defined that deserve the attention of both academia and practitioners:

1. It appears crucial to embed any attempt to minimize land consumption by spatial planning in a strategy that at the same time eliminates existing incentives for land-consuming development. It is therefore important to identify and then tackle such incentives in, for instance, tax policies or policies for structural development.
2. Given the variety of regulative planning instruments it would be worthwhile to scrutinize the feasibility and effectiveness of possible combinations of different instruments. In this vein, the thorough evaluation of management and containment policies that already exist in different states or regions will be particularly instructive.
3. Since the minimization of land consumption is largely dependent on the political will to achieve this task (which is often lacking), the provision of powerful tools to monitor land use changes and to assess their various impacts is essential. Therefore, current efforts in land use science to develop such tools that are easy to handle and allow establishing the overall effect of land-consuming activities can provide a major contribution to the minimization of land consumption.
4. The ongoing attempts to seek for scientifically sound arguments in favor of compact urban development can supply the efforts to minimize land consumption with weighty arguments.

Finally, it is always important to acknowledge the particular context in which the minimization of land consumption is to be achieved. The existence of a similar set of regulatory means in different countries, for instance, is by no means tantamount to their practical relevance also being similar in these contexts. Likewise, the perception of urban form and density patterns or the reaction of people to anti-sprawl campaigns may vary considerably from place to place. Against this background, it is virtually impossible to transfer planning strategies and instruments by means of which authorities try to minimize land consumption from one legal and cultural context to another without further ado. Therefore, it remains a major research task to keep an eye on practical experiences regarding the applicability of planning strategies and instruments in different contexts as this will provide a basis for their adaption to the context in which they are to be utilized. Without such effort to allow for the particularity of different contexts it seems hardly possible to control, manage, and steer the development of fresh land to the most acceptable locations and to minimize land consumption, and thus to increase the sustainability of land use patterns.

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Landscape Planning for Sustainable Water Usage

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Article Outline

Glossary

Catchment (or river basin) The drainage area of a stream, river, or lake. It has a common outlet for its surface runoff.

Ecosystem An arbitrary ensemble of macroscopic matter that captures, stores, and uses energy to circulate and rearrange matter within the system.

Evaporation (of water) (1) The emission of water vapor by a free surface at a temperature below the boiling point. (2) The amount of water evaporated.

Interception loss Rainfall evaporated from canopy and litter.

Landscape The traits, patterns, and structure of a specific geographic area, including its biological composition, its physical environment, and its anthropogenic or social patterns. An area where interacting ecosystems are grouped and repeated in similar form.

Landscape ecology The science of studying and improving the relationship between spatial pattern and ecological processes on a multitude of landscape scales and organizational levels. Landscape ecology is highly interdisciplinary and integrates biophysical and analytical approaches with humanistic and holistic perspectives across natural and social sciences.

Landscape structure, function, and pattern structure Is determined by the composition, the configuration, and the proportion of different patches across the landscape, while *function* refers to how each element in the landscape interacts based on its life-cycle events. *Pattern* is the term for the contents and internal order of a heterogeneous area of land.

Landscape planning The aspect of the land use planning process that deals with physical, biological, esthetic, cultural, and historical values and with the relationships and planning between these values, land uses, and the environment.

Landscape water balance Inventory of water based on the principle that during a certain time interval, the total water gain to a given catchment area or body of water must equal the total water loss plus the net change in storage in the catchment or body of water. In hydrology, a water balance equation can be used to describe the flow of water *in* and *out* of a system. A *system* can be one of several hydrological domains, such as a column of soil or a drainage basin.

Scale A definition applied to the time, space, and mass component of any quantity is that scale denotes the resolution within a range of a measured quantity. This definition encompasses two important, interacting facets of scale: resolution and range. Resolution or "grain" refers to the finest distinction that can be made in an observation set, while range or "extent" refers to the span of all entities that can be detected in the data.

Transpiration Process by which water from vegetation is transferred into the atmosphere in the form of vapor.

Definition of the Subject and Its Importance

Extreme events such as floods, droughts, as well as water scarcity and poor water quality have been increasing globally during recent decades. Global change phenomena, increasing population density in some parts of the world, as well as multiple land use of

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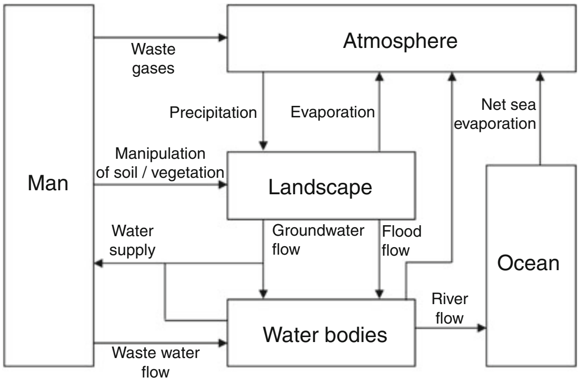
landscapes such as agricultural management, urbanization, and industrialization are some of the main reasons for these problems. Both the mentioned reasons as well as the resulting environmental consequences, represent some of the world's most pressing problems that occur on different scales – from the field to the region or even globally. In recent decades, integrated river basin and environmental management – including landscape planning – have been introduced as a potential but challenging instrument to tackle these complex transdisciplinary problems around the world. However, several problems still exist before an effective integrated planning and management can be realized. This section introduces these problems and presents contributions to the solution for some of these (methodological but also environmental) problems. In the following, the existing problems and needs of the handled topics are briefly argued, and numerous studies on the solutions to these problems are shortly illustrated. In the sense of an integrated methodology, promising developments of decision-support systems are presented as one future direction to support sustainable land use planning and water resources management. Finally, criteria for sustainable water planning are presented.

Introduction

"Water is life. It nourishes our ecosystems, powers our industry, grows our food, and makes life itself possible" [1]. This statement emphasizes the importance of water for humans and nature. The human factor "land use" affects the interactions between the components of a landscape structure in different manners and intensities. Landscape pattern or structures consist of water, soil, geomorphology, vegetation, etc. Water-carried fluxes of matter (nutrients, sediments) and energy play an important role for the landscape balance. All components of the landscape structure are interrelated by these fluxes. Hence, society needs a way to handle a landscape as a whole, so that the human manipulative capabilities do not have too much head start over our knowledge about the impacts of these manipulations [2].

However, extent and rate of effectuate changes in landscapes still exceeds, to a high degree, the scientific capability to reliably predict long-term impacts of technological developments on natural cycles and



Landscape Planning for Sustainable Water Usage. Figure 1
The continuous water flow through the water cycle, linking sea evaporation, atmospheric vapor flow, moistening of continental landscapes, recharge of aquifers and rivers, and outflow to the ocean ([1], see also [7])

processes. Human impact not only on landscape pattern, water balance, material fluxes, habitats for plants and animals, but also on socioeconomic situations has in fact reached a degree that may lead to irreversible changes and put at risk the natural systems essential for life support. Thus, landscape ecology and other environmental sciences have to develop suitable and improved methods to assess the impacts of anthropogenic changes in landscapes and to develop a conceptual base for sustainable land use.

Land use is the parameter by which society controls the landscape water balance [3]. It controls not only parameters such as evaporation, surface runoff, or groundwater recharge in catchments, but also soil erosion and water quality. Figure 1 shows the complex interrelationships within the water cycle. The water cycle links evaporation from the sea, atmospheric water vapor flow, the moistening of continental landscapes, the recharge of aquifers and rivers, and the river discharge back to the sea. The human physical and chemical interventions (including land use in all its forms) influence the atmosphere, the landscape, and the aquifers and rivers [1]. Hence, the investigation of the effect of land use change and land use patterns on the water resources provides information for the development of sustainable land use concepts and integrated environmental and river basin management as demanded by landscape programs or political directives. Examples for such directives are the Clean Water Act [4] in the USA or the European Water Framework Directive (WFD; [5]) in Europe. Due to the oftentimes insufficient water availability or poor water quality of the streams these environmental programs were implemented to achieve good ecological and chemical conditions of water quality of groundwater and surface water bodies.

In addition to these directives, land use plans (for different scales such as communities, counties, states, or even nations) based on ecological principles (landscape ecological plans) are finding increasing application, especially in continental Europe and the USA [6]. This reflects a growing maturity in landscape ecology, enabling it not only to inform theory, but also offer solutions to "real-world" planning problems. In countries with a long history of industrialization, visual distinctiveness and biodiversity have been severely eroded by a combination of habitat removal and fragmentation, intensive farming and forestry, river engineering, transport corridor construction, and industrial pollution and dereliction. More subtle effects, associated with pollution and nutrient transfers by air and water, have also had significant impacts [6].

On the one hand, the spatial distribution of different land use types (settlements, forest, grassland, pasture, arable land) affects the water and nutrient cycle of a landscape, but on the other hand also the different types of land management (crops, tillage, etc.) are important factors that influence these cycles. Table 1 gives an impression on the percentage of soil evaporation, interception loss, and transpiration of different land uses and land cover on the total evaporation.

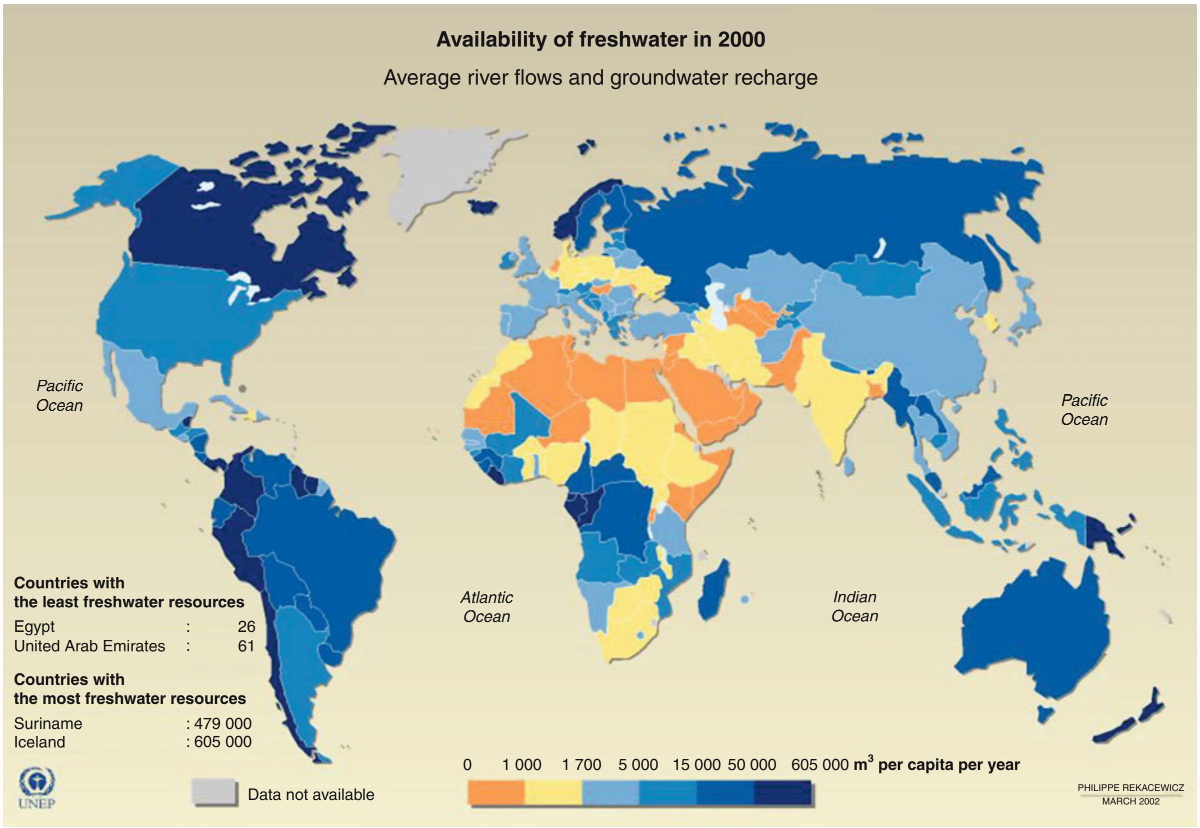
Landscape Planning for Sustainable Water Usage. Table 1 Percentage of soil evaporation, interception loss, and transpiration of different land uses and land cover on total evaporation [8]

	Soil evaporation	Interception loss	Transpiration
Forest	–	40%	60%
Pasture	15%	25%	60%
Arable land	30%	15%	55%
Bare fallow	100%	–	–

Sustainable land use and management needs a sound knowledge of these influences. Hence, there are numerous examples for studies described in literature where measurements and computer-aided hydrological models are applied successfully for the simulation of the influence of land use and management changes on potential groundwater recharge or streamflow. Mostly variants or scenarios are investigated that are based on assumptions of climatic change or of the influence of political decisions. When simulating water balances for large areas, only considerable land use changes result in noteworthy shifts of the simulated total runoff. Depending on the selected model type, database and regional site conditions of the study site, land use changes can affect the results (and also the further modeling) to varying degrees. The assumptions of land use changes can be made on the basis of plausibility considerations, or models can be applied [9]. Overviews of the prospects and limitations of eco-hydrological models for evaluation of land use options in mesoscale catchments are given by Fohrer et al. [10] and Hörmann et al. [11]. On the one hand, such influences of land use and management have to be reduced that have a negative impact on the water resources. On the other hand, land use and management can be used as instruments to realize sustainable landscape development. The complexity of these interrelationships on different scales makes its study extremely challenging. The examples presented in this chapter are mainly from the "developed" world, such as from Europe, the USA, or Australia. Despite existing problems, the presented examples in these regions are with no doubt "best cases" for landscape planning and sustainable water planning. However, especially in the developing regions with an increasing number of drought and flood events and water quality problems, there is an urgent need for integrated landscape and water management strategies [1]. This becomes even more important with regard to the enormous regional differences of water availability in the world (as presented Fig. 2). Figure 2 shows the global distribution of water availability at country level.

Processes and Planning on Different Scales

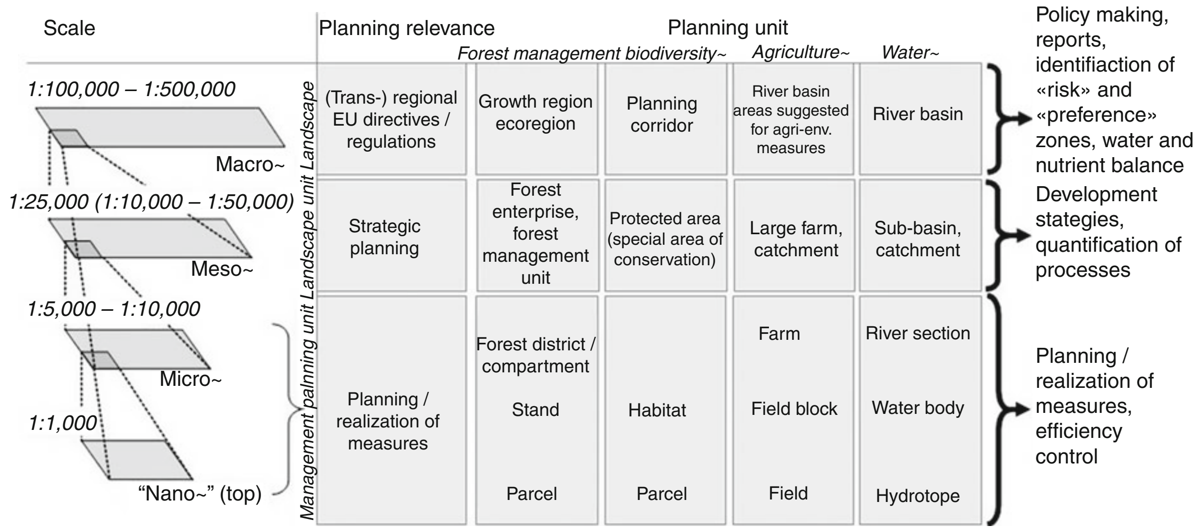
Land use affects the interactions between water, soil, geomorphology, vegetation, etc., on several scales in



Landscape Planning for Sustainable Water Usage. Figure 2
Availability of freshwater through average river flows and groundwater recharge, in cubic meters per capita per year, at the national level in the year 2000. The graphic highlights the countries with the least freshwater resources (Egypt and the United Arab Emirates) and those with the most (Suriname and Iceland)

different manners and intensities. That means that both natural processes and environmental problems occur on different spatial and temporal scales, from the field to the region, and even globally [12–15]. Due to the long tradition in scale-specific research in landscape ecology, several methods are available for the investigation of landscape ecological structures and processes on, for instance, fields or farms (the microscale), where the processes have to be measured or mapped, as well as for the whole world, where for instance climate is simulated by using General Circulation Models (GCMs). Only a few studies deal with the optimization of the scale-specific applicability of these methods and models, especially for larger scales [16–18]. But most of the environmental changes and conflicts between land use, conservation, and resource management become obvious at the so-called landscape scale [19]. Special attention should be paid to the investigation of the landscape water balance – at least in temperate and humid zones, because water-carried fluxes of matter and energy play an important role for the landscape balance . All components of the landscape structure are interrelated by these fluxes. Therefore, special indicators and model applications have to be developed for landscape-scale investigations that allow assessments and forecasts about the impacts of land use changes on the landscape balance.

Several papers from different scientific disciplines deal with the hierarchical organization of nature [20]. An overview about hierarchical concepts in landscape ecology is given by Klijn [21]. These concepts are mainly focused to the hypothesis that each of the scale levels (micro-, meso-, and macroscale) is characterized by specific temporal and spatial ranges.



Landscape Planning for Sustainable Water Usage. Figure 3
Scales and planning units in forestry, biodiversity, and agricultural and water management

Landscape Planning for Sustainable Water Usage. Table 2 Hierarchies in landscape and spatial planning in Germany (after [27])

Scale level	Planning level	Spatial planning	Landscape planning
Macroscale	Country	Spatial development policy	–
Mesoscale	Federal scale Region	*Raumordnungsplan* *Regionalplan (= regional planning program)*	*Landschaftprogramm* *Landschaftsrahmenplan (= landscape program, landscape framework plan)*
Microscale	Municipality (town, village) Parts of municipalities	*Flächennutzungsplan* *Bebauungsplan (= land development plan, zoning plan)*	*Landschaftsplan* *Grünordnungsplan (= landscape plan, green structures plan)*

As a consequence, each scale level needs data layers with suitable spatiotemporal resolution and specific investigation methods and provides specific knowledge [22]. The main topic here is the definition of a linkage of the different landscape scales. The main hypothesis of the hierarchical approach suggested by Steinhardt and Volk [17, 23] is that the basic components for vertical and horizontal material and energy fluxes – morphology, soil, hydrology, land use and land management, and climate – are similar over all scale levels. It is only the importance of the factors of these components that changes for each scale [24]. To give an example for morphology and erosion: On the local scale, surface roughness is one of the main factors that will affect erosion disposition, whereas for larger scales (up to river catchments) the factors slope inclination, slope length, slope exposition up to the shapes of streamlet, -net, -order, and direction of flow are responsible for erosion processes.

According to the hierarchical organization of nature spatial planning and forest, biodiversity, agriculture, and water management are also organized hierarchically (Fig. 3, Table 2). In Germany, regional management plans are instruments within the spatial planning system used to set guidelines for landscape development on the regional scale. Priority areas for "landscape functions " are designated at the community level. But there are only few applications of landscape ecological information – especially about the regulation capacity – that are included, and the realization of sustainable development requires the recognition of all landscape functions. Therefore, useful indicators and parameters have to be derived for analyzing and optimizing the regulation and production functions of the existing landscape types for the concerned scales [25, 26].

Effects of Land Use Pattern on the Hydrological Cycle

Measurements

The impact of land use and land cover change on the hydrological cycle can be quantified by using different methods – depending on topic and scale one is interested in. One way to quantify the impact of vegetation cover change on the hydrologic cycle is paired watershed experiments [28, 29]. In a paired catchment experiment, land use is held constant on the control catchment and changed on the treatment catchment. Differences in hydrologic response with respect to annual runoff, flood, and low flow response and water quality can then be compared for catchments experiencing the same weather patterns [30]. Hibbert [31] gives a summary of 39 catchment experiments. He concluded that the reduction of forest cover increases water yield and in contrast the establishment of forest cover on sparsely vegetated land decreases water yield. The response to treatment was highly variable and thus for most parts unpredictable. Bosch and Hewlett [32] added another 55 catchment experiments to this review and sorted them by mean annual precipitation, vegetation type, and country. They confirmed the first two statements of Hibbert [31] and concluded that "coniferous forest, deciduous hardwood, bush and grass cover have (in that order) a decreasing influence on water yield of the source areas in which these covers are manipulated." Coniferous forest causes around 40 mm change in annual water yield per 10% change in forest cover. Deciduous hardwoods are associated with a 25 mm change in yield per 10% cover change, while bush and grassland generate around 10 mm of difference. In their data set, forest cover changes of less than 20% could not be detected by measuring stream flow. Stream flow response to deforestation or afforestation depends both on the region's mean annual precipitation and on the precipitation for the year under treatment. Yield changes are greatest in high-rainfall areas. In low-rainfall areas the effect is less pronounced but more persistent due to slow vegetation regrowth. Decreases in water yield following afforestation seem to be proportional to the growing rate of the stand, while gains in water yields after clearfelling diminish in proportion to the rate of recovery of the vegetation. Smith and Scott [33] found that the dry season flow from forested catchments was lower than from comparable non-forested catchments in South Africa. Burch et al. [34] and Peck and Williamson [35] address the hydrological aspects of forest replacement by annual crops or pasture. The latter focused on the effect of deforestation on groundwater in five Australian paired catchments (0.8–3.5 km). Clearing increased the average recharge rate documented by piezometer hydrographs. Potentiometric heads within the forest and up to 50 m down-gradient from areas that were cleared have responded to clearing after a delay of 2 or 3 years. This delay was consistent with the very low transmissivity of the aquifer under observation. Burch et al. [34] compared two experimental catchments; one vegetated by natural eucalypt forest (5.0 ha) and the other completely clear-cut and maintained in grassland (7.8 ha) for over 80 years. The grassland catchment generated high-peak storm flows and large discharge volumes irrespective of antecedent soil water content, whereas the forested catchment gave little runoff provided the antecedent soil water content was below 60% of the available storage capacity. In the case of woodland establishment a substantial reduction of runoff was reported by Williams et al. [36].

In single-catchment experiments, the effect of land use change is measured by comparing measurements before and after the change occurred. Thus it is more difficult to separate the effect of land use change from the effects of different weather patterns before and after the change. It is a common knowledge that discharge from forest, urban, and agricultural catchments is different, but the experimental quantification is still not easy. A simple, but radical solution is the clear-cut or afforestation of entire catchments [37–39]. An overview of conversion studies from and to forest is given by Whitehead and Robinson [40]. An overview of paired catchment studies, where only a part or a subcatchment is changed, was published by Best et al. [28]. Major influence factors such as soil and relief properties of the catchments are seldom discussed. Paired watershed experiments, however, were limited to a size of 1–2,500 ha.

Modeling

In larger catchments it becomes increasingly costly and difficult to control the experimental boundary conditions and to measure precipitation and stream flow accurately. Thus in recent years the application of simulation models to quantify the effect of land use change on the hydrologic cycle has increased. The first water balance models were produced back in the late 1940s. In a more sophisticated manner, the development of hydrological models started in 1960s with the Stanford watershed model [41]. Until today the number of models and model systems as well as the number of different model concepts grew considerably as indicated in the overview given by Singh [42]. They have evolved in a number of different directions depending on the many purposes for which they are required [43, 44]. Generally speaking, nowadays there are three different approaches to modeling the landscape water balance:

1. *Physical-deterministic models*, which are based on the fundamental laws of physics (chiefly hydrodynamics and thermodynamics), chemistry, biology, etc.
2. *Conceptional models*, which take these laws into account in a simplified manner and also use empirical approaches
3. *Empirical-statistical models*, which are solely based on the empirically measured cause–effect relations of system inputs and outputs without trying to fathom the laws on which they are based

The transitions between the three approaches are in a state of flux. Moreover, hydrological processes always include both deterministic and stochastic characteristics owing to the unavoidable simplifications of complex reality and the error occurring when capturing input data [45].

Depending on the model type and its purpose, different scales of temporal and spatial resolution are used. Compromises usually have to be made between the accuracy desired and the availability of data. If nonlinear processes are being studied (e.g., precipitation and runoff), hourly or daily steps have to be used, whereas for seasonal or annual properties monthly or even yearly steps suffice. The possible degree of spatial resolution ranges from highly aggregating approaches in which the study area is divided into a few subunits with similar geophysical properties ("lumped models") to models that as far as possible take into account the variability of spatial structures ("distributed models"). The scope for using a higher spatial resolution has improved with the advent of faster, more powerful computers, the development of geographic information systems, and – especially recently – the growing availability of data stored in a Geographical Information System (GIS).

Water balance models are used to depict the impact of land use changes on potential natural groundwater recharge (e.g., [46, 47]). Usually variants or scenarios are investigated, which are for instance based on assumptions concerning climatic change or the impact of political decisions (Table 3). If balancing is performed over the entire study area, only very pronounced land use changes will result in any considerable shifts in the simulated total runoff. What the list in Table 3 fails to show are any local changes, which in certain areas may well considerably exceed the means calculated. The algorithm used to introduce the land use changes forecast into the area also needs to be considered. Depending on local characteristics, the effect on further modeling exerted by a change in land use varies greatly. Assumptions regarding the spatial distribution of land use changes can be made by using plausibility considerations. Alternatively, models can also be used [9].

Hydrologic models can be useful tools to evaluate the effect of landscape patterns or land use change resulting from policy decisions, economic incentives, or changes in the economic framework [9, 50, 51]. One of the earliest works was from Onstad and Jamieson [52], who investigated the effect of land use modifications on runoff. A two-dimensional groundwater model has been applied in several Australian experimental catchments to quantify the response of the underlying aquifer to the removal of deep-rooted native vegetation [53]. The catchment response to

Landscape Planning for Sustainable Water Usage. Table 3 Case studies on land use change and water yield [48]

Region	Scenarios in the case studies	Land use change	Simulated change in total water yield (%)	Reference
NE-Germany	EU agricultural reform	Change of 4% AL into forest, change of 32% AL into forest	−1, −10	[49]
Hesse (Germany)	Agricultural policy: grassland premium	Forest: 42→13%,	+8	[9]
		AL: 44→73%		
Hesse (Germany)	Agricultural policy: cessation of animal husbandry	Forest: 42→49%,	+2	[9]
		AL: 44→37%		
Saxony-Anhalt (Germany)	Analysis of land use conflicts in priority areas (agriculture vs. groundwater protection)	Change of 10% AL into forest, *Koethener Ackerland, Noerdlicher Mittelflaeming*	−9, −2	[47]

AL arable land

clearing was assumed to be a function of the temporal pattern of the clearing, the proportion of the catchment cleared, the location of the clearing within the catchment, and the rainfall amount. Calder et al. [54] carried out a modeling study to determine the effects of land use change from natural forest to agricultural land on a large-scale catchment (124,500 km) in Africa. Lørup et al. [55] applied the lumped conceptual hydrologic model NAM in six medium-sized catchments (200–1,000 km) to assess the long-term effect of land use change in Zimbabwe. They stated that despite a significant increase in population density, there have been no major changes in the percentage of each land use type and thus there was no indication of increased surface runoff in the six catchments. The physically based model SHETRAN [56] was applied to characterize the influence of land use on catchment hydrology [57]. Results from those simulations show that the same land use change may have a significant effect on the hydrology of a lowland subcatchment, but an insignificant effect on the hydrology of the upland subcatchment. This underlines the necessity of spatially distributed modeling approaches for land use change studies.

Dunn and Mackay [57] discuss in detail the influence of vegetation type on evapotranspiration and its components' interception and transpiration for the Tyne Basin (>2,000 km) in northeast England. They outline the importance of physical soil properties for the nature of the hydrological response to variations in vegetation cover. Lahmer et al. [58] and Eckhardt et al. [59] addressed the problem of input data uncertainty for land use change studies in large catchments.

Another crucial point is the thorough validation of catchment models for predicting land use change. In large basins there are usually no experimental data for real land use change available. Thus the model calibration and validation is mostly restricted to measured stream flow data. Different validation techniques are discussed critically by Klemes [60] and Ewen and Parkin [61]. Additional information for model testing can be obtained by the application of base-flow separation algorithms, as for example, as proposed by Lyne and Hollick [62] or Arnold et al. [63]. Though one has to be aware that this method is empirically based and thus the applicability to catchments other than those of the original data set is limited, and the results should be interpreted with care.

Land Use as Controlling Factor for Water and Nutrient Dynamics

The investigation of the effect of land use change and land use patterns on hydrologic processes such as groundwater recharge or surface runoff provides information for the development of sustainable land use concepts and integrated environmental and river basin management as demanded by the landscape programs or the European Water Framework Directive (WFD [5]). There are numerous examples for studies described in literature where hydrological models are applied successfully for the simulation of the influence of land use changes on potential groundwater recharge or streamflow. Mostly variants or scenarios are investigated that are based on assumptions of climatic change or of the influence of political decisions. When simulating water balances for large areas, only considerable land use changes result in noteworthy shifts of the simulated total runoff. Depending on the selected model type, database, and regional site conditions of the study site, land use changes can affect the results (and also the further modeling) to varying degrees. The assumptions of land use changes can be made on the basis of plausibility considerations, or models can be applied [9]. Fohrer et al. [10] and Hörmann et al. [11] give an overview of the prospects and limitations of eco-hydrological models for evaluation of land use options in mesoscale catchments. The papers that they analyzed are classified into three categories: analysis of consequences of observed (or historical) land use changes on the water cycle, simulation of hydrologic consequences of land use change based on ecological and mainly economic scenarios, and finally optimization of land use according to economic or ecological criteria, where both components, hydrology and land use change, are simulated.

Lorz et al. [48] emphasize the need of an improved consideration of the spatial distribution and functionality of forests in river basin management. Their review of relevant papers has shown that forests, despite their frequent occurrence in temperate zones, play presently only a minor role in river basin management. In general, most of the studies highlight the positive effect of forests on water and nutrient fluxes in river basins. But hydrologists have also reported consistently flood events in or originating from forested areas. In context of the discussion on forest ecology and water quality it became obvious that forest ecosystems can be sources depending on system properties, time, and atmogenic pollution. The simulation of land use changes on water yield in forested river basins has been carried out in a great number of research projects, but mostly without considering the spatial distributed function of forests. The objective of Lorz et al. [48] was thus to improve the consideration of spatial distribution of forests in river basins and its effect on water yield and water quality. The most promising approaches in the future are either spatial explicit models or integrated models with both improved forest modules and landscape positioning. The efficiency of these models could be proved by using virtual catchments. As a first conceptual approach towards the base concept of a virtual catchment, they propose a five-unit model (FUM), representing cross-sections with typical land use sequences. The basic idea of their model is to identify major process units and to implement them in the river basin modeling and management.

In much of Europe, the USA, and parts of Australia, increased inputs of especially nitrogen and phosphorus to land in the form of fertilizers, manures, and biosolids means that agricultural runoff now comprises a greater share of these nutrients in groundwater, rivers and lakes, and associated water quality problems [64, 65]. Numerous site-specific field studies have quantified the potential export of nutrients in agricultural runoff. But it is clear that to meet the requirements of end users, the research effort needs to shift towards developing suitable models that are based on expert knowledge to simulate the impact of land use and land management practices on diffuse source pollutant transport. Franko et al. [66] and Neubert et al. [67] give examples for the application of two different model systems: the process-based carbon-and-nitrogen-dynamics models, CANDY, and the (balance-oriented) whole-farm simulation model, REPRO, to determine land usage variants, which, employing the regional regulation potential, lead to a reduction of nutrient outputs into neighboring ecosystems. The hydrological effects were simulated with ABIMO (which is a runoff generation model) that was used to model data for groundwater recharge. This was then taken as a basis in conjunction with area-related nutrient balances to estimate nitrogen discharge by using the model CANDY (***C****arbon-and-****N****itrogen-****Dy****namics*; [66, 68]). With regard to the modeling and estimation of the scenario effects, extensive sensitivity analyses were carried out. As a result not only point estimates for the criteria values were generated but also probability distributions reflecting various kinds of data and model uncertainties [69]. The results of the studies presented by Volk et al. [70] and Franko et al. [66] were used as a basis for multi-criteria ecological-socioeconomic assessments described in Horsch et al. [71] and Klauer et al. [69]. The application of an alternative model combination of ABIMO and the model REPRO (Reproduction of Soil Fertility; Hülsbergen [72]) in this study area is presented in Neubert et al. [67]. Models such as REPRO provide efficient tools for evaluating both environmental and economic performance of farming systems. The results indicate an explicit dependency of the nitrate leaching on groundwater discharge and nitrate balance in relation to the variants of cultivation practice like organic, integrated, and conventional farming. The work shows clearly the influence of the quality and availability of data on the simulation results, whereas the model structure seemed to have less influence in this case study.

The experiences of different European and national projects dealing with the model-supported implementation of the WFD revealed that the available *integrated* model systems are still far from being suitable for operational applications with regard to water quality simulations [73–75].

However, complex transdisciplinary problems have to be tackled through implementation of WFD or other environmental directives. Hence, in order to achieve optimal working efficiency of the models in the management processes, it is required that they contribute information over a wide range of abiotic and biotic aspects of hydrology and water quality demanded by the decision makers, which cannot be achieved by individual groundwater, water quality, or erosion models. Consequently, the suitability of the publicly available river basin model Soil and Water Assessment Tool (SWAT) [76], the available database and the existing water quality monitoring network to adequately represent general trends in water quality changes resulting from various measures based on land use and management change in the intensively used Upper Ems Basin was checked by Volk et al. [18, 77, 78] and Ullrich et al. [78].

During the last years, increased cultivation of energy crops influences the landscape water and nutrient balance. Schilling et al. [79] showed that over the last century, land use and land cover (LULC) in the US Corn Belt region shifted from mixed perennial and annual cropping systems to primarily annual crops. Historical LULC change impacted the annual water balance in many Midwestern basins by decreasing annual evapotranspiration (ET) and increasing streamflow and base flow. Recent expansion of the biofuel industry may lead to future LULC changes from increasing corn acreage and potential conversion of the industry to cellulosic bioenergy crops of warm or cool season grasses. Schilling et al. [79] used SWAT to evaluate potential impacts from future LULC change on the annual and seasonal water balance of the Raccoon River watershed in west-central Iowa. Three primary scenarios for LULC change and three scenario variants were evaluated, including an expansion of corn acreage in the watershed and two scenarios involving expansion of land using warm season and cool season grasses for ethanol biofuel. Modeling results were consistent with historical observations. Increased corn production will decrease annual ET and increase water yield and losses of nitrate, phosphorus, and sediment; whereas increasing perennialization will increase ET and decrease water yield and loss of nonpoint source pollutants. However, widespread tile drainage that exists today may limit the extent to which a mixed perennial-annual land cover would ever resemble pre-1940s hydrologic conditions. Study results indicate that future LULC change will affect the water balance of the watershed, with consequences largely dependent on the future LULC trajectory.

Scale Appropriate Application of Models for Integrated Ecological-Economic Assessments and Decision-Support

Integrated river basin and environmental management involve all management objectives related to the use, pollution mitigation, pollution rehabilitation, protection and rehabilitation of water bodies, as well as many other impacts on biodiversity, soil protection, water quantity, and quality in river basins or administrative units [80]. An integrated approach implies that relations between the abiotic and the biotic part of the various water systems, between ecological and economic factors, and between various stakeholder interests are considered in decision-making processes. It takes into account three often conflicting main dimensions: ecology, economy, and equity [81]. Directives such as the WFD, the NATURA2000 in Europe, or Clean Water Act (CWA) in the USA call for multidisciplinary approaches of river basin and environmental management. Hence, during recent decades a number of research projects have developed (spatial) decision-making support systems (DSS) for integrated water resources and environmental management (including socioeconomic analyses) with respect to groundwater management and flood prevention problems [80–87]. Most of them offer the possibility of drawing information from geographical information systems and/or supplying interdisciplinary multicriteria analyses of the hydrological, ecological, and economic consequences of different management strategies, based on either pre-calculated scenarios or model coupling [88]. References [81] and [86–89] give examples and overviews of the development, application, and potential of different types of DSS. Giupponi [86] states that despite the many DSSs developed in the field of environmental management, the risk of Decision Support Systems failing to meet the challenge of real-world problems is reported to be high, and even the criteria for judging whether a DSS has been successful or not are often a matter of discussion (e.g., [90–92]). He emphasizes that there is a widely recognized need to develop new decision-support tools in this field, with greater attention to the needs of potential users and to identification of the application context.

An integrated approach to catchments, that is, administrative units, is essential that would include a necessary basis for balancing and reconciling conflicting interests. Therefore further development of integrated natural resource management is needed to incorporate land use, pollution leads, and vital ecological goods and services [1]. Planners and policy makers have the difficult task to intervene in complex human–natural systems. They cannot focus only on individual processes; rather it is necessary to address the system as a complex integral whole and think about economic values. To fulfill these requirements, tools such as DSS that integrate environmental, social, and economic concerns and that facilitate the involvement of interested parties in the formulation of strategies may be useful. Especially water is considered more and more as an economic good due to competing water use resulting in resource scarcity (e.g., [93–95]). Decision makers need information about the economic value of water and the economic consequences of water management. The complexity of interactions between water, ecology, and the economy can be captured through formal, mathematical models. These models link relevant hydrological and biogeochemical processes to economic "laws" of supply and demand underlying the provision of scarce water services. Brouwer and Hofkes [95] edited a special issue on "Integrated hydro-economic modeling: Approaches, key issues and future research directions" in the journal of "Ecological Economics." They distinguish between main approaches: modular, holistic, and computable general equilibrium models. The latter top-down models counterbalance the traditional emphasis on bottom-up water engineering approaches. Key issues and future research directions in integrated hydro-economic modeling are discussed and illustrated through a variety of case study applications worldwide. Although the interaction works both ways, feedback effects of water changes on the economy and changes in the economy on the water system are often missing in practice.

The study presented by Rode et al. [96] includes the work on integrated nutrient transport modeling with respect to the implementation of the WFD that was done in the Weisse Elster Case Study, Germany. The implementation of the WFD can only be tackled by comprehensive environmental and economic assessments based on an integrated methodology and decision-support system. The methodology was developed within an interdisciplinary research project on the highly polluted Weisse Elster River basin, a large subcatchment of the Saale basin that is part of the UNESCO-IHP HELP program. The project focuses on nutrient management, river basin management, and decision making to achieve good ecological status of surface waters. From the modeling study using SWAT it can be concluded that the investigated organic farming scenarios do not ensure a considerable reduction in high nitrogen loads from the agricultural land of the studied catchment. Only the scenario on liberalization of the agricultural market leads to a considerable reduction in nitrogen loads due to large reduction of agricultural land use of 42.6%. The scenario analysis shows that sufficient reductions in nitrogen loads with respect to the ambitious goals of the WFD can only be achieved with a considerable change in agricultural land use. With regard to the river water quality modeling study it can be concluded that the impact of the most feasible measures on the concentration of inorganic nitrogen is quite low. Little effect on the yearly mean of inorganic phosphorus is also expected. The reason for this is that the autotrophic assimilation is low and the substance regimes between sediments and the water column are on average balanced, since the seasonal dependence of fixation through sorption or mobilization by desorption or erosion is preponderant. The parameter uncertainties are high and sometimes larger than the effect of the investigated river restoration management scenarios. The case study shows that easily applicable measures for the reduction in diffuse nutrient (especially nitrogen) loads may not be sufficient to reach the goal of good water quality status requested by the WFD.

Volk et al. [18] present the results of the FLUMAGIS project, in which they developed a spatial decision-support system (SDSS) to support the implementation of the WFD. The main objective of the WFD is the achievement of a good ecological and chemical status of the water environment (water bodies). This status corresponds to the limit value of Germany's Working Group of the Federal States on Water Problems Issues (LAWA) for water quality class II (3 mg/l total nitrogen). The rivers in the intensively cropped Upper Ems River basin (Northwestern Germany) show total nitrogen concentrations in excess of 5–10 mg/l. One objective of the project was to find a land use and land management scenario that would reduce the total nitrogen concentration to meet the WFD requirements for good ecological and chemical status [77].

Within the FLUMAGIS project, Volk et al. [77] developed consecutive land use and management scenarios on the basis of policy instruments such as the support of agro-environmental measures by Common Agricultural Policy and regional landscape development programs. The model simulations were done by using SWAT. Table 4 summarizes the

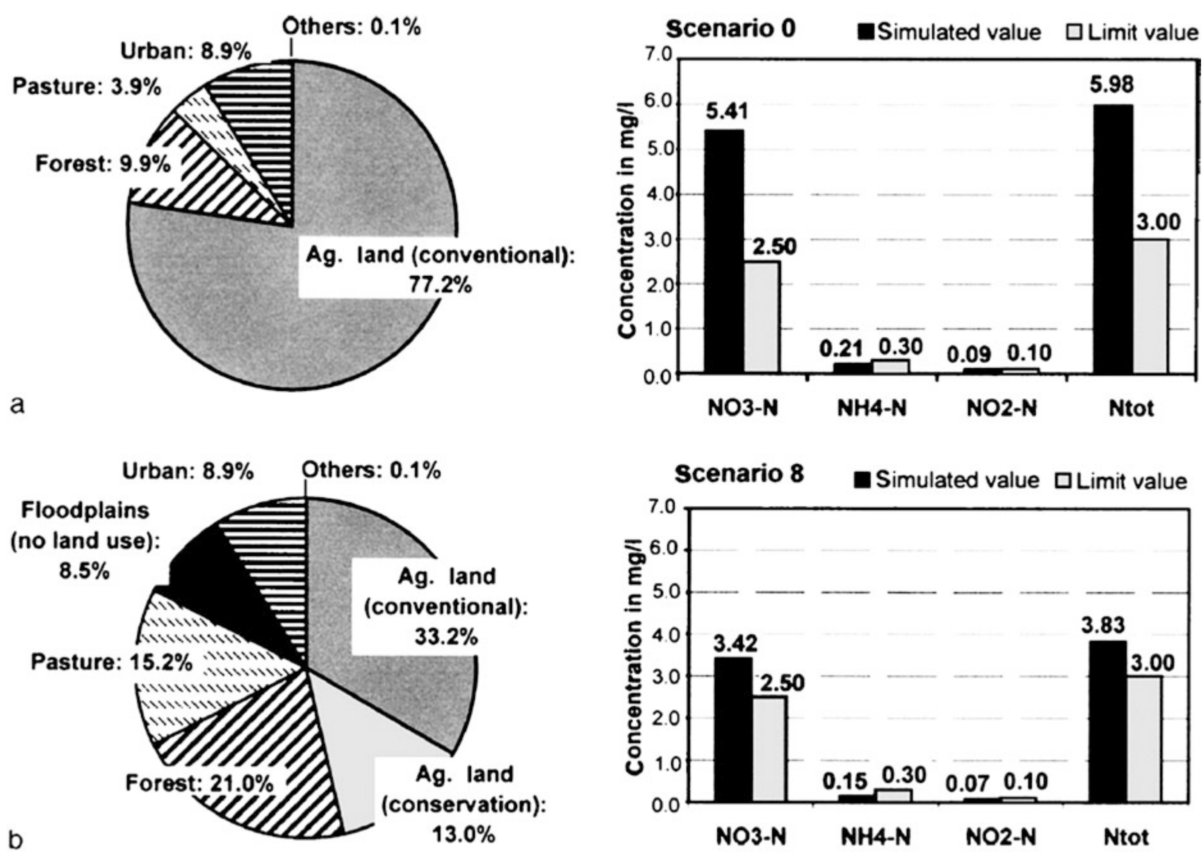
Landscape Planning for Sustainable Water Usage. Table 4 Implementation of agro-environmental measures in the model

Scenario	Measure	Implementation in the model
1	Increase of pasture/decrease of arable land	Modification of the land use file (shape-files). Allocation of the land use type pasture on former arable land.
2	Extensification of pasture	Reduction of livestock density to 1.4 livestock units per hectare by modification of the management scenarios. Reduction of the amount of fertilizers.
3	Afforestation of arable land	Modification of the land use file (shape-files). Allocation of the land use type forest on former arable land.
4/5	Implementation of conservation tillage practices Extensification of arable land Modification of crop rotation schemes	No plowing, only cultivator and harrow (reduction of tillage depth), reduction of mixing efficiency. Reduction of the amount of applied mineral fertilizers accordant to 0.7 livestock units. Implementation of complex management scenarios over several years with short fallow periods.
6	Oxbow reconnection (improvement of river morphology) Riparian buffer strips	Increase of the river length on the HRU level. Modification of Manning's roughness coefficient "n" (CN_N(2)) for main channel flow. Modification of the parameter FILTERW
7	Abandonment of the floodplain use	Conversion of arable land and pasture in riparian zones to areas without management. Change of floodplain pasture into wetland (according soil and groundwater conditions).
8	Additional increase of pasture/decrease of arable land	Conversion of arable land to pasture (randomly chosen).

agro-environmental measures that they considered in the model. They were developed successively in direction of a target scenario that finally would come close to the water quality objective of the WFD. The areas for the necessary land use changes were mainly chosen by catchment characteristics (permeability of the soils, groundwater table) and the degree of human impairment (river channel regulation, nutrient leaching).

In order to achieve the good ecological status for nitrogen at the Upper Ems River, the nitrogen concentration has to be reduced by 50% of the mean annual average. This would require substantial, expensive changes of land use and land management intensity as well as of the river morphology. Figure 4a, b shows the current conditions and the target scenario (scenario 8) that comes closest to the requirements of the water quality class II for nitrogen.

In addition to river channel changes, this scenario includes reduction of arable land from 77.2% to 46% (13% organic farming), increase of pasture from 4% to 15%, afforestation from 10% to 21%, increase of protected wetlands from 0% to 9%, etc. However, this is not realistic from an economic point of view, since the drastic cuts for the farmers would be so strong that most of them would have to give up their farms. Agro-economic calculations have shown, for instance, that the mentioned changes in the floodplains alone would cost between 500 and 800 euro per hectare per year (31.6 million euro per year) [18] depending on regional soil qualities and management intensities.



Landscape Planning for Sustainable Water Usage. Figure 4
Current land use distribution and nitrogen concentrations (**a**) and scenario 8 (**b**) with the land use distribution and simulated nitrogen concentrations to achieve the good ecological status for the Upper Ems River. Note values include 0.26 mg organic nitrogen for (**a**) and 0.2 mg/l organic nitrogen for (**b**)

This measure is expected to result in intense conflicts with affected farmers [18].

Results of SWAT scenario calculations showed that drastic measures, which are unrealistic from a socioeconomic point of view, would be needed to achieve the water quality target in the basin. The example shows additionally that the achievement of the WFD targets is only possible with a consideration of regional landscape and land use distinctions. A related problem yet to be addressed is the general lack of measured water quality data with which to calibrate and validate water quality models such as SWAT. This adds considerable uncertainty to already complicated and uncertain situations. Thus, improved strategies for water quality monitoring, and data accessibility must be established.

Future Directions

Landscape planning and sustainable water use can only be successful within integrated approaches. In this regard, integrated landscape and river basin management takes into account the three often conflicting dimensions of ecology, economy, and equity [81]. Finding a proper balance between the interests of different stakeholders requires understanding the effects of combined measures on multiple river functions [97]. Uncertain future conditions related to changing political priorities, economic development, and climate change influence the outcome of proposed alternatives. The decisions are inherently a political (and economic) matter, but resulting management plans need scientific underpinning and the support of local stakeholders prior to implementation. There is a need to (a) bridge the gap between the scientific knowledge and demand for information (that requires a combination of a wide range of expertise and data) and (b) make the information available for the analysis and presentation of promising strategies for integrated landscape and river basin management. The benefit of using DSSs in the complex field of integrated landscape and river basin management is that these systems enable comparisons of different land and water management strategies based on the effects on multiple objectives.

With regard to DSS, Volk et al. [98] analyzed benefits and shortcomings of four recently developed decision-support systems. The analysis elaborated on the following aspects: (1) application area/decision problem, (2) stakeholder interaction/users involved, (3) structure of DSS/model structure, (4) usage of the DSS, and finally (5) most important shortcomings. On the basis of this analysis, they formulated four criteria that are considered essential for the successful use of DSS in landscape and river basin management. The criteria relate to (1) system quality, (2) user support and user training, (3) perceived usefulness, and (4) user satisfaction. Volk et al. [98] could show that the availability of tools and technologies for DSS in landscape and river basin management is good to excellent. However, their investigations indicated that several problems have to be tackled. First of all, data availability and homogenization, uncertainty analysis and uncertainty propagation, and problems with model integration require further attention. Furthermore, the appropriate and methodological stakeholder interaction and the definition of "what end users really need and want" have been documented as general shortcomings of all four examples of DSS. They propose an iterative development process that enables social learning of the different groups involved in the development process, because it is easier to design a DSS for a group of stakeholders who actively participate in an iterative process. Volk et al. [98] also identified two important lines of further development in DSS: the use of interactive visualization tools and the methodology of optimization to inform scenario elaboration and evaluate trade-offs among environmental measures and management alternatives.

In general, new approaches to long-term water planning and management that incorporate principles of sustainability and equity are required and are now being explored by national and international water experts and organizations. Hence, Gleick [99] offered seven sustainability criteria for water planning (Table 5).

These sustainability criteria provide a framework for prioritizing competing interests and for making decisions about future water use and management. The first two criteria require that basic allocations for humans and ecosystems are identified and met, which are to be satisfied before other demands. Thus, the approach suggested by Gleick [99] defines criteria for basic needs as recommended by Agenda 21 of the

Landscape Planning for Sustainable Water Usage. Table 5 Sustainability criteria for water planning [99]

A basic water requirement will be guaranteed to all humans to maintain human health.
A basic water requirement will be guaranteed to restore and maintain the health of ecosystems.
Water quality will be maintained to meet certain minimum standards. These standards will vary depending on location and how the water is to be used.
Human actions will not impair the long-term renewability of freshwater stocks and flows.
Data on water resources availability, use, and quality will be collected and made accessible to all parties.
Institutional mechanisms will be set up to prevent and resolve conflicts over water.
Water planning and decision making will be democratic, ensuring representation of all affected parties and fostering direct participation of affected interests.

United Nations. Besides setting out quantity and quality requirements, they also set an upper limit to water use and provided some institutional guidance.

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Landscape Planning/Design of Shrinking Landscapes

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Article Outline

Glossary

Demographic change Refers to new demographic developments that bring sustained sub-replacement fertility, a multitude of living arrangements other than marriage, the disconnection between marriage and procreation, and no stationary population. Instead, populations would face decline if not complemented by new migrants, and they will also be much older as a result of lower fertility and additional gains in longevity. Migration streams will not be able to neutralize aging, but stabilize population sizes. Demographic change brings new social challenges such as aging, integration of immigrants and other cultures, less stability of households, and high levels of poverty or exclusion among household types like single persons of all ages or single parents. It brings alterations in per capita housing and transport demand.

Ecosystem services Society benefits from a multitude of resources and processes that are supplied by natural ecosystems and landscapes. Collectively, these benefits are known as ecosystem services and include products like clean drinking water or recreation area and processes such as the decomposition of wastes. In 2004, the United Nations 2004 Millennium Ecosystem Assessment (MA) formalized ecosystem services and grouped them into four broad categories: provisioning, such as the production of food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefits.

Governance Governance is the activity of governing. It relates to multi-actor and multilevel decision-making that define expectations, grant power, or verify performance. It consists either of a separate process or of a specific part of management or leadership processes. In the case of a nonprofit organization, governance relates to consistent management, cohesive policies, processes, and decision rights for a given area of responsibility. In case governance refers to land use, it deals with land management.

Landscape planning Landscape planning puts landscape ecology into a spatial planning context. It focuses on landscape function and ecosystem service assessment on different spatial scales. Landscape planning develops strategies for sustainable land use systems including the whole range from natural, cultural landscapes to impacted or devastated areas.

Land use Land use is the human modification of the natural environment, surface, or wilderness into built environment such as fields, pastures, and settlements. Urban land use is characterized by a particular high degree of imperviousness.

Perforation Development of patchwork settlement structures without a compact core and related creation of low-density counter settlements with implications for lower sealing rates, building and population densities. The spatial cohesion of perforated areas is low.

Shrinkage Shrinkage is understood primarily as the quantitative process of population decline in an area which might be the result of very different processes such as deindustrialization, demographic change, or even natural hazards.

Sprawl Urban sprawl is a multifaceted concept, which includes the spreading of impervious surface and

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built-up area outward of a city and its suburbs to its outskirts to low-density, car-dependent development on rural or virgin land, with associated design features that encourage car dependency.

Sustainability Sustainability is the capacity to endure. In ecology, it describes how biological systems remain diverse and productive over time. For humans, it is the potential for long-term maintenance of well-being, which in turn depends on the well-being of the natural world and the responsible use of natural resources. It includes the maintenance of landscape functions, ecosystem goods and services.

Definition of the Subject

When thinking about sustainability, it is mainly about how to keep intact nature and environmental resources for either future generations and/or, more in terms of environmental justice, for other parts of the world. Land use and spatial planning focus on how to minimize negative effects of urban and industrial growth. Set against this context, urban shrinkage represents a new challenge. This is true due to the fact that one has to deal with the opposite phenomenon of growth – population decline and accompanying processes of de-densification – which, unemotionally, also asks the same questions as even mentioned for growth: How could land use development be steered in order to ensure quality of life of the population under conditions of decline? How high-quality and sustainable urban livelihoods can be developed? Are there visions for sustainable shrinkage?

Resource consumption is a problem particularly in cities due to the concentration of population – that is consumers of environmental goods and ecosystem services. Since some years, more than half of the world population lives in cities. And, what is more, >200 cities worldwide, mostly in Europe, Russia, Japan and the US, are shrinking: they are losing population. Shrinkage and declining population numbers do not mean an automatic decrease of natural resources consumption such as land, energy, or water because the per capita requirements on environmental resources, ecosystem services, and housing space are increasing. Also, in shrinking cities, household numbers increase. In consequence, population losses along with rising per capita housing space lead to further land consumption and enlargement of, for example, transport and infrastructure. Also, in shrinking cities, sprawling settlement development continues because of specific housing preferences such as single family houses and spacious housing with backdoor garden.

Since shrinkage does not follow the logics of growth, there are no receipts for how to sustainably develop or plan a shrinking city. This entry will show that shrinkage appears in many different shapes and argues that there will not be a "one-size-fits-all" or textbook answer to this question. So doing, the entry addresses the relationship between urban decline, socio-demography, infrastructure, land use, and ecosystems, and discusses causes and consequences of shrinkage in the light of sustainability. It ends up with showing how actors in cities react to shrinkage in terms of rethinking their visions, instrumental settings, and strategic planning.

Introduction: Shrinkage and Sustainability – Setting the Scene

Urban Shrinkage

Shrinkage affects many cities across the world, especially old industrial areas (America's Rust Belt, British Midlands, Germany's Ruhr Valley, eastern part of Germany; [1, 2]). The phenomena of urban shrinkage and its concomitant industrial blight, low investment rates, depopulation, and low housing demand can be vividly exemplified in the landscape: dilapidated residential buildings and estates, extensive brownfield and derelict commercial sites, streets with vacant storefronts, underutilized social and technical infrastructure, and neglected parks and squares [3]. Shrinking cities often hold large brownfield sites, particularly in their old built-up inner parts [4].

Urban shrinkage appears in many forms and dynamics. Since their very early history, cities across the world have already seen phases of decline [5]. The same is true if one narrows the focus to look at the recent decades of urban development. Already throughout the entire twentieth century up to the present day, urban shrinkage has become reality for many cities in Europe, Russia, Japan, and the eastern US ([6]; cf. Fig. 1).

Recent studies provided evidence for the fact that about 40% of all European cities >200,000 inhabitants have lost population in a short-, medium- or long-term

Landscape Planning/Design of Shrinking Landscapes. Figure 1
World map of shrinking cities with more than 100,000 inhabitants (adopted from the "Atlas of shrinking cities" by Office Oswalt, [1])

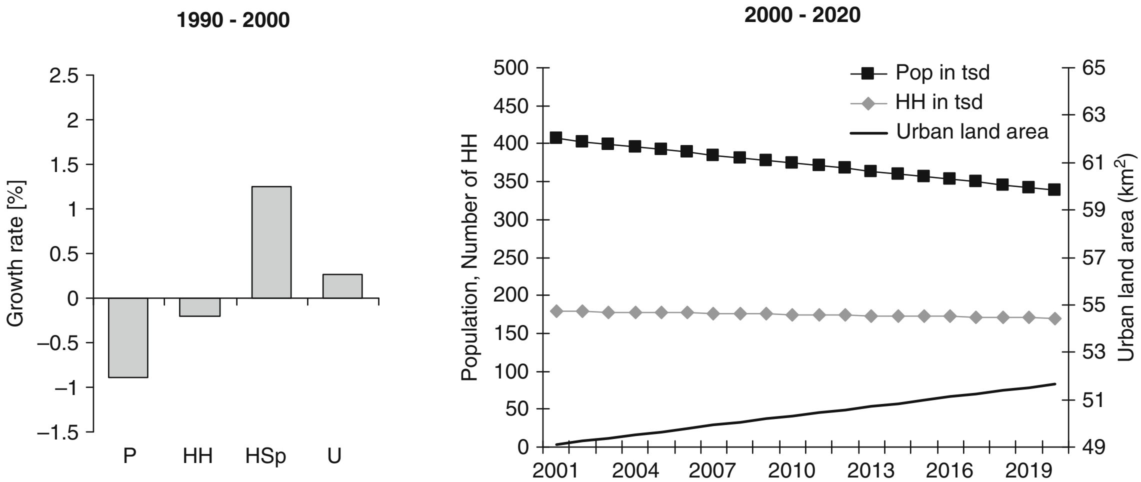
period for different reasons (for a quantitative analysis, see studies by [6] or [7]). Therefore, urban shrinkage has become the focus of international research and debate, not least because of cross-national projects (e.g., Shrinking Cities, 2002–2008; ShrinkSmart, 2009–2011) or the establishment of scholarly networks (e.g., the Berkeley Cities International Research Network SCIRN; [8]). One of the exceptional cases of urban shrinkage is eastern Germany, which lost between 10 and 20% of its residents in a period of 10 years (mean value for big cities from 1990 to 1999 is about 16%). Thus, in the following, eastern Germany will serve as an example case when analyzing processes and patterns of shrinkage.

How does urban shrinkage relate to sustainability and resource consumption in urban regions? A recent analysis of the relation of population and household development of 195 European cities from 1990 to 2000 to the growth of urban land consumption and housing space [9] found a significant share of cities facing declining population and decreasing household numbers. Nonetheless, the urban (= impervious) areas within the boundaries of these declining cities have continued to spread. No reduction of natural resource consumption in terms of returning sealed surfaces back to their natural states was observed (Fig. 2).

In addition to that, [9] identified an increase in per capita housing space, which also counteracts a reduction of land consumption. A linear projection of population, household numbers, and urban land up to 2020 shows that, exemplified at European cities, urban – that is mostly impervious surface – areas will face further land consumption, regardless of whether population and household numbers increase or decrease. Therefore, the global problem of unsustainable resource consumption seems not to be "simply" solved by population shrinkage.

Urban Sustainability

The concept of "sustainable development" evolved in response to the socio-environmental impacts of economic activities. Already in 1987, the Brundtland report framed it as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development). The application of this concept to urban regions and urban land use development raises many questions. This is, firstly,



Landscape Planning/Design of Shrinking Landscapes. Figure 2

Left: Annual growth rate of total population (P), number of households (HH), per capita housing space (HSp), and urban land area of shrinking cities across Europe 1990–2000. *Right*: Projection of total population, number of households, and urban land area of shrinking cities in Europe from 2001 to 2020. The annual growth rates were computed for each variable x as Δx from t_0=1990 to t_1=2000, for instance, for the number of households HH: $\Delta HH = HH(t_0) - HH(t_1)$. Assuming that the average aggregate population, the average household size, the average rates of urban and commercial land take in European cities in 2020 remain at the level of 2000 (t_1), the aggregate population at t_2 was estimated as $Pop_{t_2} = Pop_{t_1} + GR_{a_{1990-2000}}$ where $R_{a_{1990-2000}}$ is the average annual growth rate 1990–2000 [9]

due to the diverse concept of sustainable development, which combines economic, social, and environmental goals, both locally and globally, and in both the short and longer term [10]. And secondly, because the nature of the urban areas is generally a complex mix of drivers, pressures, and processes in many different sectors, at different spatial scales [11]. In particular, the peri-urban role is as a hinterland and support system for urban core activities [12]: food is produced there, recreational facilities are given, energy is provided, and drinking water delivered [13, 14].

There is also a global dimension to the urban sustainability agenda, which is still dominated by growth: In the next 40 years, current projections show a rapid growth in the urban areas of developing countries of up to 3 billion people [15]. Current trends show that a majority of urban residents will live in slums or chaotic settlements lacking basic infrastructure [16]. Much of this "urban" development is likely to be in peri-urban areas, or rapidly metropolitanized peri-rural areas [17]. However, next to this spreading growth, demographic aging and low-rate fertility will establish a new urban trajectory also in the developing world. This trend currently has been already reached cities in India or China [18, 19].

When thinking about sustainability, keeping intact nature and environmental resources for either future generations and/or, more in terms of environmental justice, for other parts of the world are talked about. Landscape and regional landscape planning focuses on how to minimize negative effects of urban and industrial growth [12, 20]. In terms of sustainability, urban shrinkage represents a new challenge because one has to deal with the opposite phenomenon of growth – decline and accompanying processes of de-densification and land use perforation – and focus on the following questions: How could land use development be steered in order to ensure quality of life of the population under conditions of shrinkage? Is it possible to direct land preparation toward the inner parts of shrinking cities? Are there visions for sustainable shrinkage?

Premises of Shrinkage

Urban shrinkage has been approached using different ways (see review by [8]): Some scholars interpret shrinkage as a decreasing population development in the urban core (city) as part of wider shifts in the spatial organization of larger urban regions (for example, between the urban core and the peri-urban hinterland) in the course of which existing built environments are devalorized, mainly in economic terms, and made obsolete [21–23].

Others discuss urban shrinkage as an inevitable result of uneven economic development, emerging as something rather natural that is deeply rooted in the nature of capitalist economies [24] and the underlying dynamics of the territorial division of labor [25, 26]. In fact, many shrinking cities exist because of the postindustrial shift from manufacturing (II. Sector) to service industries (III. Sector) and the IT branch (IV. Sector) followed by resulting unemployment and outmigration (such as Pittsburgh and St. Louis in the US, Manchester or Liverpool in UK). In eastern Europe and the former Soviet Union, the collapse of socialist systems led or at least importantly contributed to the decline of urban regions there [2]. Still another explanatory approach discusses urban shrinkage in the light of demographic change and relates it to low-fertility rates, changes in the household formation, and migration impact (see here [27, 28]).

In this entry, shrinkage is defined as the quantitative process of population decline. Population decline is represented by both natural decline (i.e., death surpluses) and losses by out-migration (due to suburbanization, intra-regional migration, emigration). It is frequently used as the main indicator in research on urban shrinkage, which makes the findings presented here in this respect easily comparable with other studies [1, 5, 6, 29]. Overall, shrinkage processes have drained essential resources from the urban regions (mostly the core cities), leaving the cities with a diminishing fiscal base [30].

Urban shrinkage affects the physical space, the society of a city, and the surrounding ecosystems (as well as landscapes) whose mutual fit is diminishing; this leads in turn to phenomena such as mismatches of supply and demand in various respects [31]. Since shrinkage is also a spatial phenomenon, it is important to differentiate between urban shrinkage as a process and its results that are seen as reconfigured or reshaped urban structure or patterns [32]. Urban shrinkage impacts on nearly every sphere of urban life: municipal budgets, land use and urban planning, natural resources, ecosystem services, infrastructure and amenities, housing market and housing mobility, labor market and employment, residential composition, and social inclusion and cohesion. This makes shrinkage a challenge for both landscape planning and sustainability research.

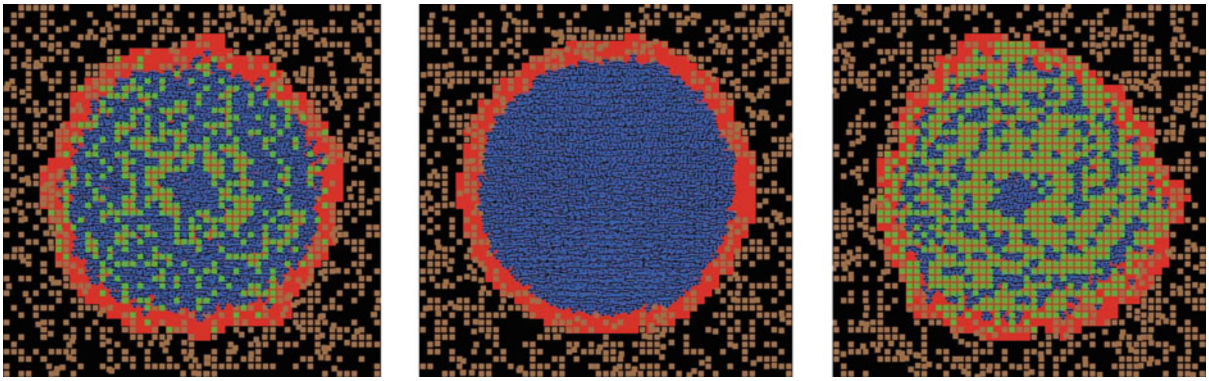
Consequences of Shrinkage on Sustainability

Shrinkage Patterns and Consequences for Urban Land Use

Population decline leads to a decrease in population density and to an oversupply/underuse of urban, residential, and commercial land, infrastructure, and services. Shrinking populations need fewer and modified services and amenities according to the need of the remaining, often aging, population [32]. This leads to problems for both the public and private sector: Underuse of the building stock leads to housing and commercial vacancies and to a more rapid dilapidation of unused buildings [33]. Whilst in some places, buildings are demolished to "balance" the housing or real estate market, in other places they simply become unusable after a certain time of not being used. [34] introduced the term of "land use perforation " in order to describe the scattered land use development in the inner parts of shrinking cities: Fig. 3 displays a stylized example of land use perforation in comparison of dense (left) and compact (center) urban forms. The simulation results show that despite population decline and decreasing demand for housing space in the inner city, land consumption at the urban periphery continues.

Table 1 provides a detailed overview on the most important processes and impacts of urban shrinkage. It gives a short explanation of the underlying processes. Figure 4, developed based on the Table 1 findings, shows that most of the processes are interrelated and shape the specific appearance or trajectory of shrinkage in a particular city [35]. It shows the fortunes of urban neighborhoods as home or place to work which depend on their attractiveness under the condition of supply surplus, on ownership structures, housing policies, and the local economic situation of enterprises and retail.

Compared to the regular patterns of land use perforation produced by the stylized model given in Fig. 3, often, differences between neighborhoods in a shrinking city vary on a small scale within the urban area [36]. This makes it extremely difficult to identify an overall



Landscape Planning/Design of Shrinking Landscapes. Figure 3
Stylized representation of urban form: (*left*) a medium density built-up town, (*center*) a very compact city, and (*right*) urban land use perforation. Blue houses represent the built-up area, red patches newly prepared peri-urban land, green patches green area, and brown patches other types of land in the rural surroundings (NetLogo model and draft: D. Haase)

picture or specified model of urban shrinkage and its impact on the city as a whole or land use patterns in a larger scale as well as in the future [2, 37].

In consequence, the change of land use causes an increasing proportion of derelict land or brownfields within the inner parts of the city. This can foster out-migration decisions of those who do not want to live close to dilapidating building stock or areas of urban wilderness [4, 38]. This cycle will reinforce itself over time and lead to a steady decrease of population density either in specific parts of a city (Fig. 5 "perforated city"), in the central (Fig. 5 "disperse city") or peripheral parts (Fig. 5 "compact city"). In addition to such a patchy way of shrinkage, a widespread and overall decrease of population density across the entire urban area can be found [5].

The project "Leipzig 2030" [39] compared population densities of specific housing forms under conditions of high and low demand (Table 2). Low demand leads to vacancies in the buildings and to a shift of lower population densities in the city. So, for example, partial vacant, old built-up multistory estates almost "reach" population densities that are typical for terraced row houses. This is important for infrastructure development, as, normally, population density determines the network of social and technical infrastructure in cities.

Effects on Socio-Demographic Sustainability

Can a city consistently lose population and yet maintain a high quality of life, human well-being, and social equity for all groups of residents? This paper argues it cannot in case planning does not counteract the following trends discussed in the literature or shown by statistical data: Urban shrinkage leads to shifts in the population structure since out-migration is almost always selective and often removes the younger and well-educated parts of the population leading to an enforced aging of the remaining population (cf. again Table 1; Fig. 7b). The same happens when a city loses population due to death surpluses [40]. In shrinking cities, there is often a concentration of neglected population groups such as the unemployed, poor or low-income groups, and foreigners or ethnic minorities ([2]; Fig. 7c). Moreover, the overall household size is declining and accompanied by a temporary increase of the household number (cf. argumentation by [41] and [42]; Fig. 6).

This brings about challenges for social cohesion and may fix and strengthen patterns of socio-spatial and residential segregation and poverty concentration in the respective city [43]. Selective out-migration also has consequences for the labor market since skilled labor becomes scarce [8]. Here, the declining attractiveness of a city can even lead to an accelerated population loss and thus start a vicious circle [33]. In shrinking cities, high unemployment and decreasing investment are closely related to each other, which makes these cities less and less attractive for both in-migrants and developers and forces them, in many cases, into an especially developer-friendly, neoliberal

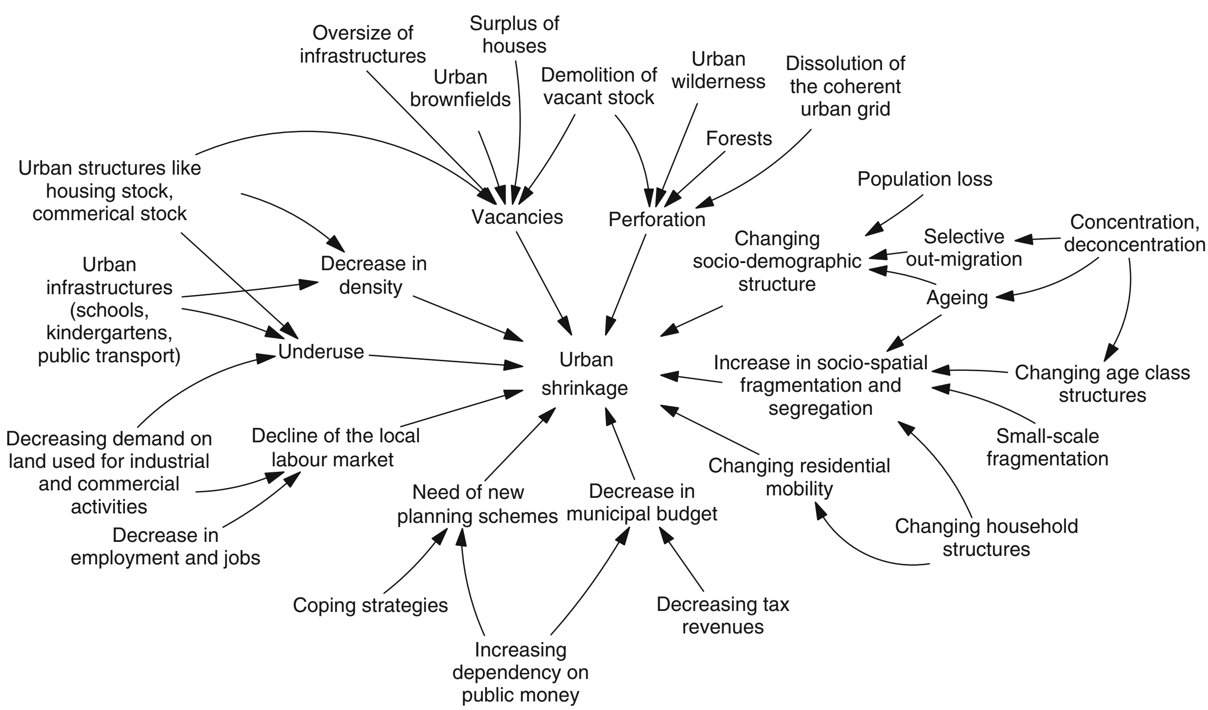
Landscape Planning/Design of Shrinking Landscapes. Table 1 Processes and impacts of urban shrinkage (adopted from [35])

Process/Impact	Explanation
Decrease in density	Population loss and out-migration lead to a decrease in the number of inhabitants of the affected areas and, subsequently, to a decrease in residential, commercial densities.
Increase in housing and commercial vacancies[a]	Decreasing demand leads to supply surplus and an underuse of housing stock, commercial stock, and, subsequently, to vacant stock.
	Vacancies in shrinking cities can affect also renovated or even new build stock due to a mismatch of supply (investment) and real demand (use).
Underuse of urban structures and infrastructures	Population losses and decrease in densities lead to an oversupply of urban structures (see above vacancies) and infrastructures such like schools, kindergartens, public transport, etc.
	Oversized infrastructures have to be either maintained without being used or closed or demolished.
Increase of unused (built) urban land	Due to decreasing densities and increasing underuse or nonuse, the share of unused built urban land increases.
	Demolition activities are necessary and being done.
	Unused built urban land can be vacant buildings, urban brownfields on former industrial, commercial, railways sites, etc.
	Unused built urban land develops to "new urban wildernesses" or even "forests".
Perforation of urban structures	Demolition, abandonment of places and uses within a city lead to the dissolution of the street or block grid of a city or urban area due to vacant lots and brown- resp. greenfields that separate or divide built lands (perforation).
	Perforated areas are characterized by a large percentage of vacant areas within an urban territory or city.
Changing sociodemographic structure of the residential population	Population losses and selective out-migration lead to aging, changing household structures, and a "blurred" age group distribution.
Increase in socio-spatial fragmentation and residential segregation	Selective out-migration and population losses might lead to a "blurred" socioeconomic structure of the remaining inhabitants.
	In shrinking cities, there are often relations between dilapidating areas with high housing vacancies and a concentration of disadvantaged population groups living there.
	Shrinking and resurging areas are situated closely to each other (= rising small-scale fragmentation).
Change in housing mobility within the city and its region	An oversupply of housing might lead to a higher housing mobility and a greater choice for a number of residential groups.
	The level of housing mobility increases due to the greater choice and the good opportunities to get a better flat at many places in the city.
	Vacant housing offers the opportunity for transitory housing, which might become more and more important for residential areas with housing oversupply.

Landscape Planning/Design of Shrinking Landscapes. Table 1 (Continued)

Process/Impact	Explanation
Decrease in municipal budget	Happens due to the decrease in tax revenues as a consequence of population losses. Results in many cases in an increasing dependency on public money.
Need of new planning schemes	Growth-oriented planning schemes have to be replaced by a strategy that aims at the coping with urban shrinkage, either in a long-term perspective or as a phase of urban development that has to be quickly overcome (depending on the causes of shrinkage and the chances of the particular city to reach regrowth).
Shrinkage of the local labor market	Decrease in employment and jobs leads to a decreasing demand on land used for industrial and commercial activities.

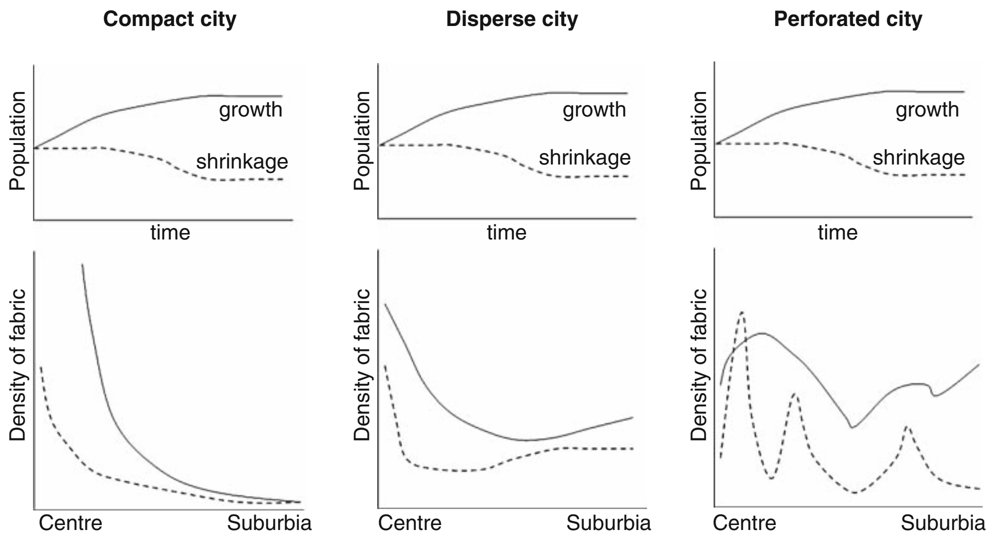
[a]Housing and commercial vacancies = housing and commercial stock that is inhabitable and useable but not inhabited or used; perforation = dissolution of the street or block grid of a city or urban area due to vacant lots and brown- resp. greenfields that separate or divide built lands



Landscape Planning/Design of Shrinking Landscapes. Figure 4
Compilation of social science indicators about shrinkage, its drivers, processes, and impacts (draft: D. Haase)

policy to attract investment. This in turn demands low wages and high land consumption at the urban periphery [38, 44].

Figure 7 provides a mapped vision of socio-demographic and land use changes provoked by shrinkage in Germany for 2020 [45] when it is defined as population decline: Fig. 7a shows the overall population decline in shrinking regions. Figure 7b then provides evidence that those regions faced with strong population decline – that is northeastern and central



Landscape Planning/Design of Shrinking Landscapes. Figure 5
Stylized urban-to-rural gradient of growing (*black* line) and shrinking (*dotted* line) population development (*upper* diagrams) and respective impacts on urban fabric density (draft: D. Haase). Such fabric densities were already observed in several eastern German but also US cities [1]

Landscape Planning/Design of Shrinking Landscapes. Table 2 Population density of different housing form under conditions of high and low demand [39]

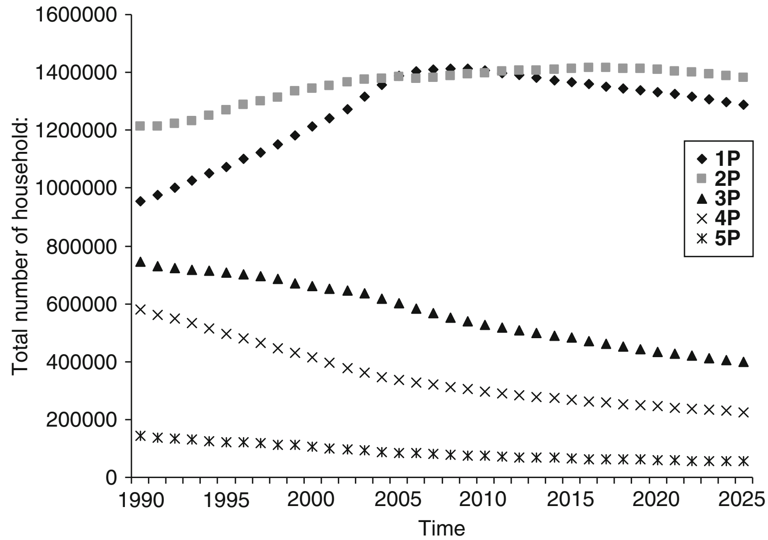
Housing form	Old built-up multistory high demand	Old built-up multistory low demand	Prefabricated multistory high demand	Prefabricated multistory low demand	Row houses	Single houses
Population density (inhabitants/km^2)	149	80	230	75	55	37

eastern Germany – age dramatically. Due to outflow of the young and well-educated people, the unemployment rate increases (Fig. 7c) – this process reinforces the aging. In consequence, settlement and transport development weakens (Figs. 7d and e), which is not by far a problem for the regional sustainability. Thus, reinforced processes of shrinking shape larger regions such as given in Fig. 7f.

Effects on Infrastructure

As far as urban space and its amenities and infrastructure are concerned, population losses bring about a decrease in density and an increasing underuse of infrastructure, urban land, and amenities [46]. Shrinking populations demand fewer services and amenities leading to problems for both the public and private sectors. Underuse of the building stock leads to housing and commercial vacancies and to a more rapid dilapidation of unused buildings [47].

So, for example, shops have to close when there is no longer enough purchasing power, and in most cases public infrastructure sees a thinning-out process – the frequency of services decreases and selected stops and trajectories are close down [48]. Local suppliers of water and electricity face a decreasing demand, which might lead to rising costs for those who still live in areas with a shrinking population, as they still have to cover



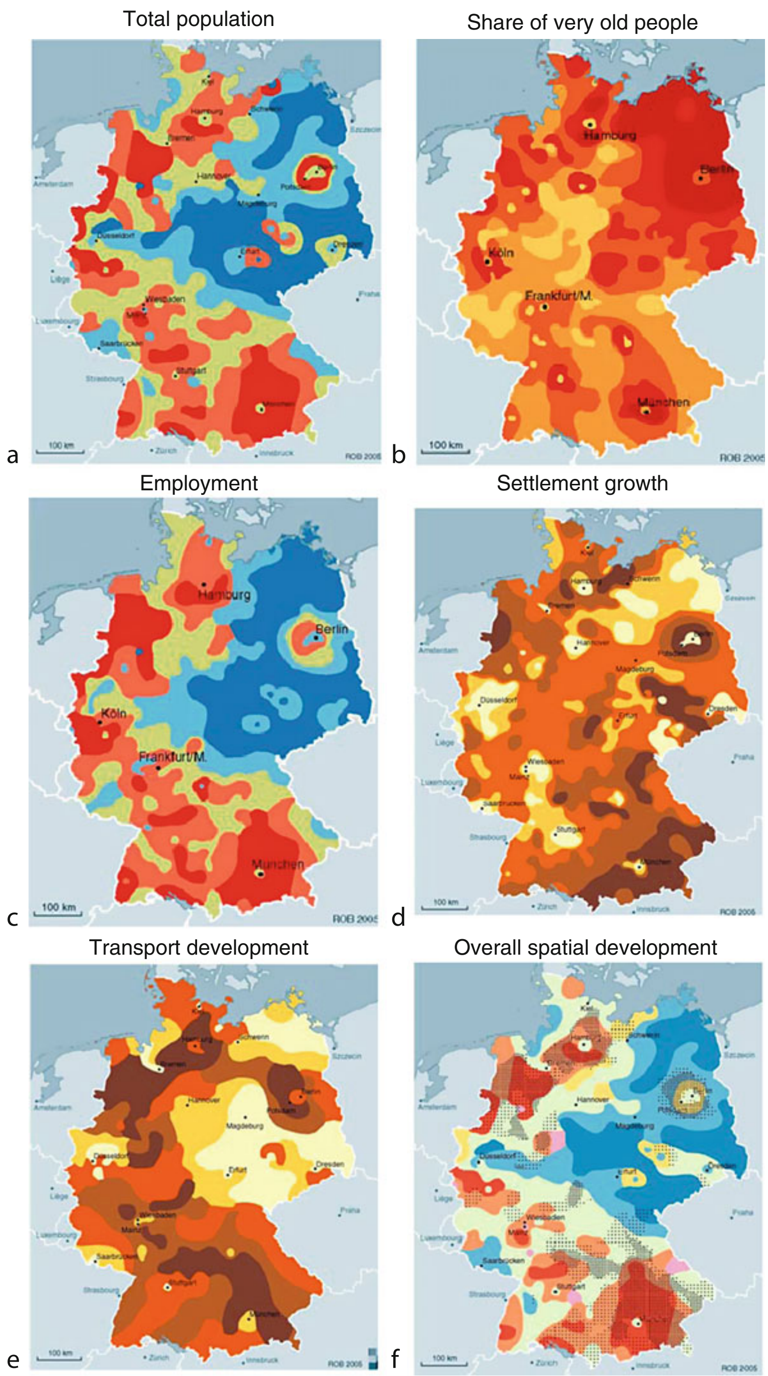
Landscape Planning/Design of Shrinking Landscapes. Figure 6
Development of the total number of households in the shrinking eastern German urban region of Leipzig-Halle measured for 1990–2005 and simulated until 2025 (own analysis based on data by the German Federal Agency for Spatial Planning). The figure shows that particularly the number of large – that is 3 and more person households (3–5P) – will steadily decline whereas one (1P) and two person households (2P) still grow for a while. This is not an effect induced by shrinkage but by demographic transition processes. Both processes overlap in shrinking urban regions

the maintenance costs of the infrastructure system [49]. Whilst to some extent a decreasing building stock density leads to "relaxation" for a densely built city, at a later stage, it might lead to a fragmentation and even the aforementioned perforation of urban space in terms of dissolution of the street or block structure due to vacant lots [33].

The – at least temporary – result of shrinkage, as discussed in the previous section, is a pattern of (newly) built-up area in rather close vicinity to vacant housing. City intervention programs finally lead to the partial demolition of the vacant housing stock and to land use perforation [33, 50]. This pattern of vacant, demolished, and new housing poses challenges for urban infrastructure provision. This is obvious for network-dependent infrastructure, like water, sewage, or electricity: Vacant houses no longer need supply of water or electricity or a transport for waste water, so that the pipes and cables leading to this house are no longer used. In an area with a larger proportion of vacant houses, underutilization can pose severe problems for maintenance of the service for the whole area [51, 52].

Social urban infrastructure like schools, kindergartens, as well as roads and public transport also are influenced by vacancy. All of these infrastructures are optimized for a certain demand structure in an area, usually determined by population density and commercial or industrial activity. At least, efficiency decreases in areas with higher rates of vacancy [2, 49]. At the worst, an area might enter a vicious cycle of declining population, underutilized and then dismantled infrastructure, so that the area gets less attractive. Thus, even more residents relocate to another part in the city [52]. Moreover, underutilization causes toxic effects and water resources pollution [46, 49]. In the years to come, housing service and maintenance costs are likely to rise in shrinking or perforating communities. In shrinking cities, lower residential densities may demand a smaller road network. Ironically, the demand for public transit could increase in shrinking cities as populations tend to be increasingly poor and increasingly without access to private transportation [2].

To avoid or at least limit higher ancillary costs and the consequent worsening of local conditions in the municipalities affected, low-cost urban renewal



Landscape Planning/Design of Shrinking Landscapes. Figure 7
Changes of the spatial patterns of socio-demographic impacts of population decline exemplified for Germany for the time span of 2000–2020 (BBSR, 2005): Legends in (**a**), (**c**) and (**f**) range from red = very positive to blue = very negative; Legend (**b**) is red = very high to yellow = moderate; Legends of (**d**) and (**e**) is brown = significant to beige = nearly zero. In figure (**f**), the dotted areas mean an overdimensional aging

Landscape Planning/Design of Shrinking Landscapes. Table 3 Adaptation of infrastructure networks to shrinking or perforating contexts ([33]; adapted)

Form of adaptation	Land use and transportation impact
Increasing accessibility	Increase in traffic and road network demand
Reduction	Decrease in traffic and road network demand
Centralization	Decrease in traffic and road network demand
Decentralization (local networks)	Increase in traffic and road network demand
Temporal mobile structures	Optimization of spatial structures
New structures and substitution	No effects for spatial configuration but for total net consumption

Landscape Planning/Design of Shrinking Landscapes. Figure 8
Images of demolished sites within an old built-up residential area: a recently demolished site under spontaneous succession and two planted sites serving for transition and recreation purposes now

strategies of the spatial adaptation of the technical urban infrastructure need to be set on the agenda (examples are given in Table 3). The pure demographic aspect that a change of household structures and sizes arises, independent from growth or shrinkage, implies further changes in water and energy use [46].

Effects on Ecosystems

Turning to the positive side effects of shrinkage in inner city and peripheral areas – which arguably contribute to urban sustainability – demolition and resulting brownfields should be understood as a chance for ecological restoration and development of green networks in city regions [4]. [53] and [54] found a positive correlation between the amount of urban green and the habitat suitability of urban breeding birds (such as for the Green woodpecker *Picus viridis*). Generally, urban fallow lands (such as shown in Fig. 8) are seen as niches for rare specialist species [55]. The study by [54] reports particular high neighborhood densities of breeding birds in the old built-up housing areas of the inner parts of the city. Thus, demolished sites should be left partially open in order to develop long-term hotspots of urban biodiversity.

In order to measure biodiversity effects of shrinkage, a number of recently demolished sites allocated in a densely built-up and socialist prefabricated housing estates of the eastern German city of Leipzig had been analyzed in terms of their spatial shape, configuration, and the resulting habitat quality for an open-land indicating bird species, Whitethroat (*Sylvia communis*). For the comparison of pre- and post-demolition status of about 50 sites, the following indicators have been used:

Largest Patch Index (LPI) of open land uses, Edge Density (ED), Habitat Suitability Index (HSI), and Shannon Diversity Index (SHI). In doing so, LPI is defined as

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A} * 100$$

where *a* is the area of single patches and *A* the total area. The edge density is

$$ED = \frac{\sum_{k=1}^{m} e_{ik}}{A}(10,000)$$

where *ED* is edge density, *A* the total area, and *e* the edge vector. Finally, the Shannon diversity is formally according to [56]

$$SHDI = -\sum_{i=1}^{m} p_i \ln p_i$$

where *p* is the single patch. The HSI had been calculated using the approach of the ecological niche which is formalized the $\sum$ of cells with a certain probability of species presence [53, 57]. For calculation and mapping purpose, the *Biomapper* software tool was used [58].

The results of the study are shown in Fig. 9 [59]. Edge density and patch size are the variables that most benefit from selective, single house, or block demolition compared to only slight changes in Shannon diversity due to the uniform grasslands that emerged after demolition at many sites, particularly in the prefabricated peripheral districts. For species like the Whitethroat, demolition seems to offer an increase of its preferred open habitat structures (HSI values in Fig. 9).

However, general positive or negative effects of shrinkage for urban ecosystems and biodiversity are not verified yet through empirical studies. In particular residential vacancy, simple land abandonment (excluding a de-sealing) and perforation are not subsequently followed by positive effects for nature and ecosystems. On the contrary, inefficient solutions could lead to higher environmental impact and more land consumption in shrinking landscapes when, despite an existing urban brownfield, open land at the periphery becomes sealed [4]. Processes and forms of urban perforation are assumed to have the potential to considerably contribute to structural enrichment and an increase in edge densities [60]. They let one further think about a bringing back of nature to former densely populated and built urban centers. At least "wilderness ideas" [38, 61] in urban landscapes for recreational and educational purposes are in discussion among urban planners and landscape architects.

Shrinkage in terms of demolition and land use perforation has also effects for the water regulation flows in the city such as surface runoff and evapotranspiration since they create potentials for de-sealing [62]. [50] found for demolished and regreened sites in Leipzig a decrease of the share of direct surface runoff and a higher water on-site percolation. The more the urban landscape gets perforated the higher the in situ water sink potential is.

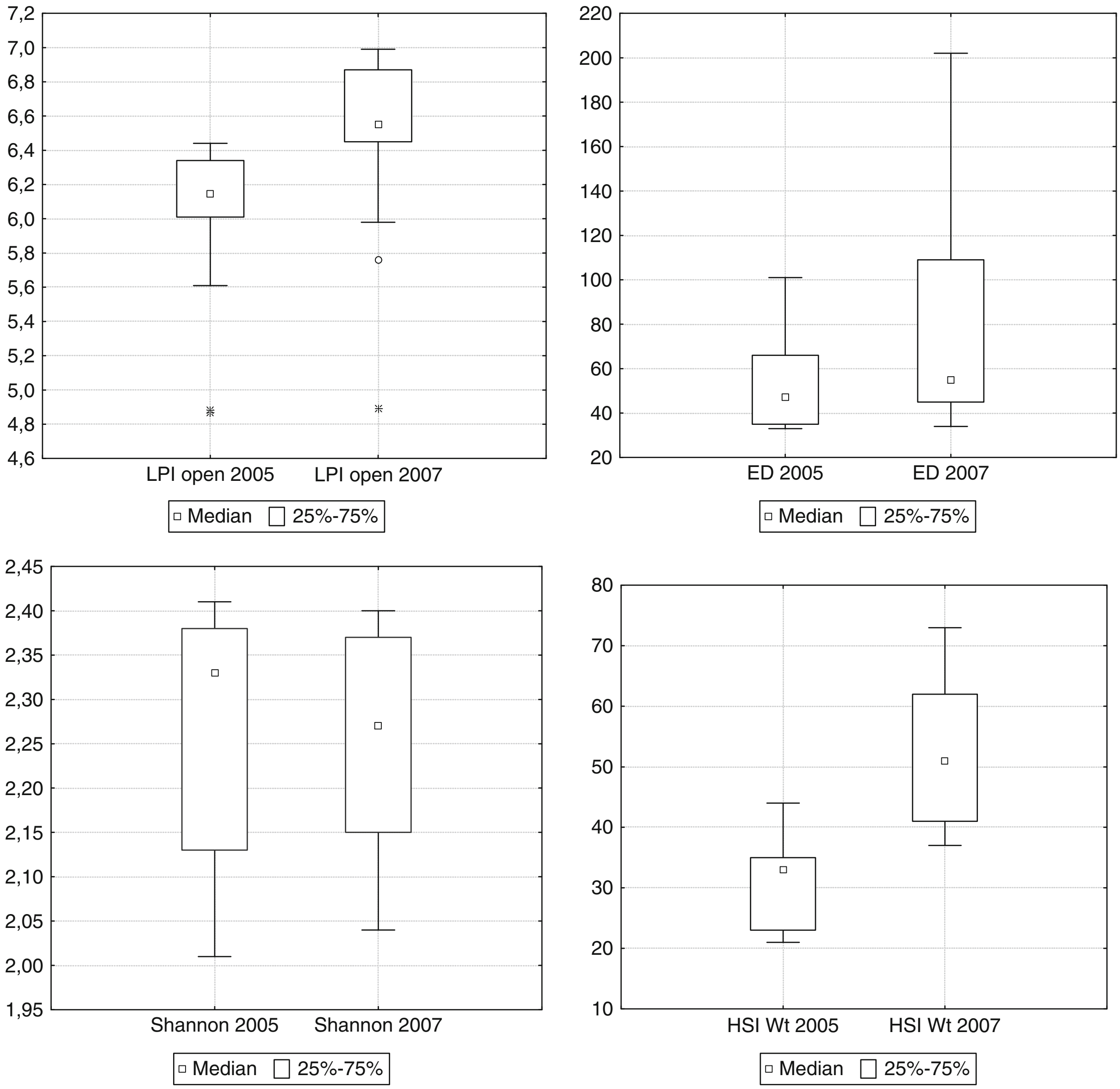
Concerning carbon storage , shrinking cities are of particular interest: they have a high potential for urban reconstruction and new green space (also as brownfields) are abundant and development pressure is low [54]. Newly planted trees unquestionably sequester atmospheric CO_2 as they grow [63–65]. As promising results of a pilot case study by [54] impressively show, tree planting at demolition sites in shrinking cities can be viewed as one contribution to the many efforts that cities have to make in order to decrease their carbon emissions.

In more general terms, next to the sequestration of CO_2 urban green can also put shade trees on vacant land [2] or cools the air by evapotranspiration fluxes [66]. To measure the climate regulation potential of urban renewal and development policies, an emissivity index value can be used for each land use in order to show differences in thermal emissions between land uses. The f-value is an approximation for the evapotranspiration potential of a land use class and therefore for emitting latent heat rather than sensible heat [66]. Table 4 shows the positive climate regulation contribution of urban renewal policies in consequence of shrinkage: They provide a higher vapor content in the air and release less heat emissions from the urban surface.

Response to Shrinkage

Modes of Collaboration and Governance

To what extent can existing planning tools used in growing communities be adapted to be used in a shrinking environment? And, secondly, how do



Landscape Planning/Design of Shrinking Landscapes. Figure 9
Largest Patch Index (LPI open) of open land uses such as park, allotment, courtyard, brownfield, wasteland, etc., Edge Density (ED), Shannon Diversity and Habitat Suitability Index (HSI) for a range of recently demolished sites in Leipzig – a comparison of the pre- (2005) and post-demolition (2009) status [59]

planners, policy makers, citizens, businesses, and others operate within a shrinking city, how do they conceptualize population decline, how do they manage the physical changes that result from shrinkage, and what can they do to plan more effectively for shrinkage? Shrinking cities might offer a paradigm shift from growth-centered planning to a more careful and place-based approach toward more livable cities [2]. But, does shrinking cities planning mean making them greener, more compact, and thus sustainable?

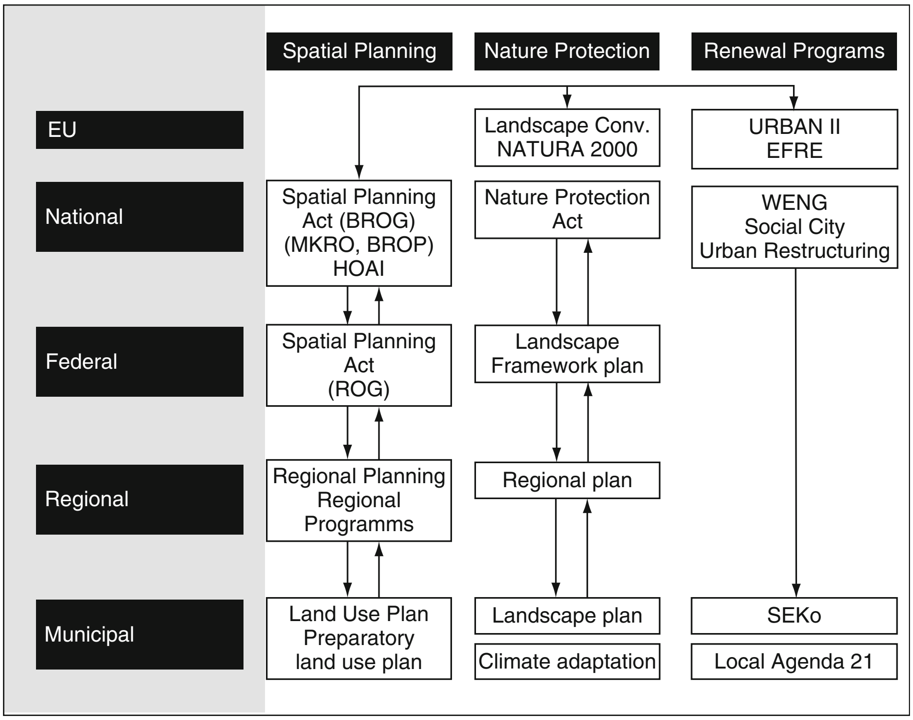
In a shrinking city, spatial planning strategies to deal with the simultaneousness of urban restructuring and population shrinkage lay a focus on enhancing the quality of life in the city as a way to retain residents.

Landscape Planning/Design of Shrinking Landscapes. Table 4 Impact of planning policies on climate regulation indicators compared to values of 2000: affected areas [km^2] for the shrinking urban region of Leipzig [66]. Urban renewal policies in bold

Climate impact	Mining redevelopment	Urban renewal	Municipal development plans	Economic land take	Green corridors	Green ring around the city
f-evapotranspiration: no change; emissivity: higher	0.0	**0.0**	8.9	0.0	0.0	0.0
f-evapotranspiration: no change; emissivity: lower	0.0	**0.0**	14.7	1.1	177.0	110.3
f-evapotranspiration: higher; emissivity: no change	0.0	**0.0**	0.0	0.0	0.8	0.0
f-evapotranspiration: lower; emissivity: no change	0.0	**0.0**	0.1	0.0	0.0	0.0
f-evapotranspiration: higher; emissivity: lower	33.0	**6.5**	13.9	0.0	12.5	53.6
f-evapotranspiration: lower; emissivity: higher	0.0	**0.0**	48.5	17.0	15.9	0.9
f-evapotranspiration: higher; emissivity: higher	0.0	**0.0**	0.0	0.0	0.0	0.0
f-evapotranspiration: lower; emissivity: lower	0.0	**0.0**	0.1	0.0	0.4	0.0
No change	999.7	**1026.2**	946.6	1014.6	826.3	868.0

They further control activities consuming land in the urban fringe to prevent urban sprawl and to direct land development to the inner parts. The spatial focus of planning strategies for shrinking cities in Germany, for example, is diverse: Formal strategies are implemented at different administrative levels, that is, municipalities, the city, regions, and the federal state. Informal strategies are frequently implemented at an intermediate level – larger than municipalities and smaller than regions. The same applies to inter-municipal cooperation, which, by definition, refers to aggregates of municipalities. There is a "gap" regarding formal planning strategies at the level of the urban landscape, which implies that well-rehearsed forms of decision-making by state actors are not prevalent here [67]. In addition to formal planning, governance – equal voice for all participants in decision-making – plays an increasing role for informal spatial planning [68], also and predominantly in urban regions. However, a sustainable future of a shrinking city can only be ensured through shared policies and planning that also involves the land owners and local entrepreneurs. Sustainable development of settlements also demands the expansion of regional cooperation across city boundaries. Wherever there are cities with excess vacant land, local entrepreneurs will attempt to extract value from such vacancy. However, local regulations, liability concerns, and the objections of nearby landowners prevent them from pursuing innovative temporary uses [2].

Shrinking cities have a range of opportunities to adapt their planning, also at very limited financial budgets: Outsourcing of urban green space maintenance, development of a more heterogeneous green network including a new complexity and disorder and the permission of more natural development. It is their chance to bring (less) people closer to nature and to involve private land owners into such programs. Strategies for integrated rural–urban development play an increasingly important role besides classic instruments, such as spatial development plans and zoning [69].



Landscape Planning/Design of Shrinking Landscapes. Figure 10
Spatial and landscape planning repertoire of Germany with respect to urban shrinkage and renewal. SEKo is the new integrated urban development plan for the city of Leipzig that acknowledges simultaneous shrinkage and growth processes

New media and formats such as planning games might facilitate an urban region's process of collectively tackling shrinkage. Models and scenarios make it easier to recognize and estimate land use potential and risks of shrinkage at an early stage [69], but they need to be accepted as communication platform by all participants, particularly local and regional stakeholders [70].

Ways of Implementation – The Pilot Case of Eastern Germany

Creating realistic visions for shrinkage is the main planning approach in eastern Germany, sponsored by the federal funding program "Urban Renewal East" (*in German* "Stadtumbau Ost"), which began in 2001 [2]. As consequence of the population decline, first of all the massive out-migration of the 1990s, eastern German cities are faced with emptying and devastated housing areas, unused infrastructure, and pattern of perforation. Urban policy makers are needed to find solutions to counteract the decline of the urban fabric and, what is more, to create urban livelihoods that "accept" shrinkage and partial vacancies as long-term phenomena. Thus, in the mid-1990s, planners started to talk about urban reconstruction and renewal realizing that prevailing urban structures did not meet the needs of a shrinking development (Fig. 10).

In this context, a set of nationally funded regeneration programs had been developed (Fig. 10): Whereas at the beginning of the 1990s "classical" programs, such as the Federal Program of Urban Renewal or WENG (a program dedicated to enhance the development of prefab housing estates) focusing on an encompassing approach of urban regeneration dominated, the situation changed after having supported the reconstruction of major parts of the eastern German core cities. The problem of a simultaneous emptying of the housing stock remained. Thus, in the late 1990s, reconstructed, old built-up housing estates were as same affected with vacancy as GDR-time prefabricated blocks.

In a second phase, urban planners initiated several new programs to find answers on this urban decline. Accordingly, "integrated programs" as a new approach in urban regeneration focusing not exclusively on the urban fabric but also on social, economic, and ecologic aspects were implemented. A couple of years ago, in 1999, the program "Social City" (*in German* Soziale Stadt) came into action foreseen to counteract the increasing social and spatial segregation as well as results of urban shrinkage and abandonment within eastern German cities. Currently, this program supports 390 initiatives in 260 German cities (www.sozialestadt.de; Fig. 10).

Set against this well-developed planning background for urban areas in the Germany after reunification, it became however clear that urban shrinkage needs specific interventions such as e.g., the opportunity of massive demolition in order to be regulated or steered (www.exwost.de). Consequently, in particular for the eastern part of Germany the intervention program "Urban Renewal East" had been implemented in 2002. To be primarily a reaction on the enormous vacancy rates the urban renewal program predominantly focused on the consolidation of the housing market aiming at a balance between housing demand and supply which is nevertheless until recently not really given: in many districts of cities like Leipzig, Chemnitz, Zwickau, Halle, or Magdeburg, the supply of dwellings outweighs the demand by far. To support the municipal housing cooperatives as well as the private house owners being economically weakened by such high vacancies is a central goal of "Urban Renewal East." In doing so, it focuses on either up-valuation of neighborhoods or on dilapidation of vacant buildings (Fig. 10).

In this vein, three different strategies had been implemented in the city of Leipzig by urban administration: one to foster urban regeneration, the already mentioned initiative "Social City" based on a manifold scenery of subsidies and, the two European programs "URBAN II" and "EFRE" came to action but these are per se spatially up-divided across the urban area of Leipzig. Thus "URBAN II" focuses on the regeneration of the western part of the city being characterized by large housing estates of the Wilhelminian style, devastated factory buildings, and large brownfields. Activities of "EFRE" and the "Social City" support urban regeneration in the eastern part of the city. In terms of urban environment, ecology, and local livelihoods, both programs fund mainly actions to improve the urban quality of life, to assist in cultural and social beliefs, and support medium and small enterprises (Fig. 10). Recently, these strategies found entrance in the new integrated urban development plan SEKo, which had been established in 2009 and covers the entire city area.

Temporary Use of Brownfields – An Innovative City Intervention Strategy

As [2] argue, less regulation and more help for grassroots experimentation may provide large new opportunities for urban regeneration in shrinking cities. One example is the temporary or interim use of vacant plots. Though temporary or interim use is not completely new (Berlin's Tiergarten after WWII, the 1st community gardens of Los Angeles, etc.), it was first employed as a formal city development strategy in the late 1990s in Germany [71]. Interim land use strategies are extolled as a cost-effective solution to fight urban blight and shrinkage. As examples in Leipzig, Berlin, and Basel have shown, interim uses have the potential to improve esthetics and perceptions of run-down areas, to increase the amount and diversity of green space opportunities and pedestrian routes, and to create new spaces for creative play and performance [71, 72], but they also have the potential to improve the environmental condition of vacant lots.

Perhaps because Leipzig was "the capital of housing vacancies" [73], it was one of the first East German cities to reorient its planning policy to confront shrinkage [3], and it did this with new district development plans, criteria for intervention intensities and priorities, innovative presentation forms, and marketing – "the perforated city" [34] and "more green, less density, greater individuality" [74] – and new planning tools like interim use.

Vacant plots of land growing wild with "weeds" are not pleasant to view for most people and contribute to negative images of neighborhoods. The situation in Leipzig was complicated by the fact that 80% of the vacant buildings and lots belong to private owners, 90% of whom live outside the city; this meant that the city had very few means with which to improve the situation [75].

Improvement of these infill sites necessitated some kind of authorization for property use. Since city acquisition of the plots could only be made in very special circumstances because of the strained municipal budget, and since expropriation is politically unpopular and in any case only possible in exceptional situations, an "authorization agreement" (*in German* Gestattungsvereinbarung) was developed as an informal planning tool to regulate limited term public use of private property while still maintaining the owner's building rights [76]. Advantages for the city include the activation of new green space for public use, connecting green space, and an assurance from the owner to ensure site maintenance, thereby improving quality of life and development attractiveness in the neighborhoods. For the owner, advantages include subsidized land clearance and development, property tax exemption for the duration of the contract, and a reduction of some running costs such as sewage or cleanup from vandalism [71].

So far, 134 public interim use agreements have been concluded for 235 plots totaling 165,905 m^2. When compared to the total area of the city's brownfields (1,942 plots totaling more than 7 million square meters), the scale of interim use agreement interventions seems small, but they are concentrated in three main intervention areas of the city, so in these neighborhoods, the impact is visible. At the program's beginning, contract periods could be for as little as 1 year, though the mean was around 8 years [76]. Now, the Saxon Urban Development Regulation has mandated a 10-year minimum contract period in order to ensure worthwhile use of state funds [71]. Despite this new restriction, interest has remained steady. Current owners under interim use contract often renew contracts because of the lack of city growth. In this sense, interim uses are increasingly becoming more permanent in nature. But what potentials and limitations does this strategy have, and how can these be measured suitably, taking into account both social and environmental factors?

[77] found that, first, interim use sites scored higher overall than their main alternative, recently demolished brownfields, especially on social criteria (i.e., accessibility, recreational interest, and use). Second, interim use sites had a much greater usage rate than other site types, especially by men. The most popular uses of interim use sites are to take shortcuts, to relax, to enjoy nature, and to walk dogs. Third, there was a wide consensus of site condition improvement over the last 6 years. Still, the most desired changes on the six sampled interim use sites are for more benches and better maintenance of the site, especially of dog litter. Fourth, most of the respondents did not know about the city's interim use strategy and do not recognize the sites as being a result of city intervention and development. In so far, it can be hypothesized that public acceptance and support for interim use might be strengthened with increased communication about the strategy and its potential as an urban planning tool [78]. This could also strengthen use by residents and willingness to participate in site development.

Future Directions

Urban shrinkage is an upcoming phenomenon cities and urban regions face, particularly in the developed world. This entry dealt with the drivers, processes, and patterns behind. Discussing the socio-demographic, land use, and ecological dimension of urban shrinkage, the entry showed the problems and threats related to population decline and economic blight. However, concerning sustainability, urban shrinkage also bears potentials and opportunities.

Urban shrinkage could allow a resurgence of nature into inner cities that are densely populated and have been built up "for ages." In this vein, ideas regarding urban wilderness for recreational and educational purposes are of concern among urban planners and landscape architects who are confronting this shrinkage. The eastern German city of Leipzig, quite a model city, has made the novel suggestion of creating urban greenery in the form of temporary green spaces at core city demolition sites as a kind of planned alternative and spontaneous and ruderal nature on former brownfields as a kind of unplanned alternative. Particularly, green spaces developed from inner-city brownfields represent "flagships" or "experimental fields" that serve as models for future greening endeavors to improve both local biodiversity and human livelihoods. Besides total demolition of houses, shrinkage also leads to a deconstruction of multistory housing stock in the form of a transition toward more spacious housing and living conditions in densely urbanized environments: bigger apartments and integrated patios and terraces, as well as higher shares of urban green and landscape within the neighborhood.

Doubtless, there is considerable potential for social, residential, and ecological improvement in shrinking cities, which, through exploring opportunities as discussed above, might attract new residents for a longer period of time and keep local dwellers in the city, instead of having them choose the detached-house alternative. This opens a new pathway to counteract urban sprawl and thus contributing to urban sustainability.

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Natural Ventilation in Built Environment

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Article Outline

Glossary

Air changes per hour (ACH) The volumetric flow rate of supply air, divided by the volume of the ventilated space.

Advanced natural ventilation system (ANV) Integration of basic natural ventilation strategies such as cross ventilation and stack effect with smart controls.

BEMS Building energy management system.

BREEAM Building research establishment environmental assessment method – UK origin.

Exfiltration/infiltration Air flow through unintended leakages out/into buildings.

Hybrid ventilation Combined natural and mechanical ventilation (also called mixed-mode ventilation).

Indoor air quality (IAQ) Indoor Air Quality – broadly defined by the purity of the air but often CO_2 is used as an indicator.

Mixed-mode ventilation See hybrid ventilation.

Natural ventilation Use of natural forces, i.e., pressure differences generated by wind or air temperature, to introduce and distribute outdoor air into or out of a buildings.

Night cooling The use of night air to cool the building using wind towers or a fan to circulate the air.

PAQ Perceived air quality.

Thermal comfort The state of mind that expresses satisfaction with the surrounding thermal environment.

Ventilation Provides fresh air into a building to ensure good air quality for occupant health and well-being.

Ventilation effectiveness The ability of a ventilation system to exchange the air in the room and also the ability to remove airborne contaminants.

Ventilation flow rate The amount of air per unit time into the ventilated space (liter per second or l/s, cubic meters per hour or m^3/h).

Well-being Healthy mind and body.

Definition of the Subject

Natural ventilation uses the natural forces of wind and buoyancy to introduce fresh air and distribute it effectively in buildings for the benefit of the occupants. Fresh air is required to achieve a healthy, fresh, and comfortable indoor environment for people to work and live in. Natural ventilation can ensure or support the supply of adequate breathing air, adequate ventilation of contaminants, adequate thermal conditioning and moisture dissipation, and contribute to well-being through a connection to the dynamics of nature. For natural ventilation to be effective, there has to be a close relationship between the architecture and the air circulation system. This includes the relationship between the built form, the site environment in a particular location, and the layout within the building.

The Natural History Museum in London, designed by Alfred Waterhouse in the Victorian age, is an excellent example of design for natural ventilation. The architect designed the built form to encourage the flow of air through each space in the building by the use of two ventilation towers at the back of the building to induce air flow through stack ventilation [1].

Buildings should be designed to take full advantage of the prevailing natural forces such as wind, outdoor temperature, sunlight, incorporating building elements such as towers, atria, and thermal mass to ventilate and

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cool occupied spaces. In many climates there is a growing proportion of naturally ventilated buildings using natural features and forces to reduce a building's *environmental or carbon footprint.*

Introduction

The reasons for ventilating a space with air are as follows:

1. Ventilation air provides oxygen that is needed for human life processes; it takes about 4 s for inhaled air to pass through the respiratory system and transfer oxygen to the blood and then to the brain; poor-quality air deficient in oxygen with consequent high CO_2 levels impedes clear thinking and concentration.
2. Ventilation air dilutes; the contaminants may be CO_2 from respiration, odors secreted through the human skin, cigarette smoke, or emissions from other process such as dust, allergens, aerosols, toxic gases, and particulates in general.
3. Ventilation promotes and directs air movement in the space, removing excessive heat and/or moisture essential for comfort and well-being.

Traditional vernacular architecture has taught us the best of sustainable architecture and ecologically sensitive adaptation, using passive features ranging from building orientation and form, appropriately sized and oriented openings linked with vertical forms, the benefits of local materials and mass for night cooling, and the relationship of buildings in context to ensure effective air flows.

Vernacular Architecture

Vernacular architecture blends buildings into their specific settings, so that there is a natural harmony between the climate, architecture, and people. Vernacular architecture learned from the environmental variations of place relating to local variations in temperature, humidity, sun, wind, rain, earthquakes, and storms. In climates where the diurnal range may be 17°C, vernacular buildings allow a variation in indoor temperature of only some 4°C through time-lag and night cooling. In climates where humidity may be 90%, vernacular buildings support human comfort by allowing air to flow over the many thermo-receptors on the human body. Vernacular architecture also adapted to ensure indoor air quality through natural ventilation through the careful design and placement of indoor pollutant generators from stoves to commodes. Four vernacular solutions are further described: wind towers and courtyards, termite mounds, and igloos, each integrating the conditioning power of natural ventilation in unique responses to local climate.

Wind Towers

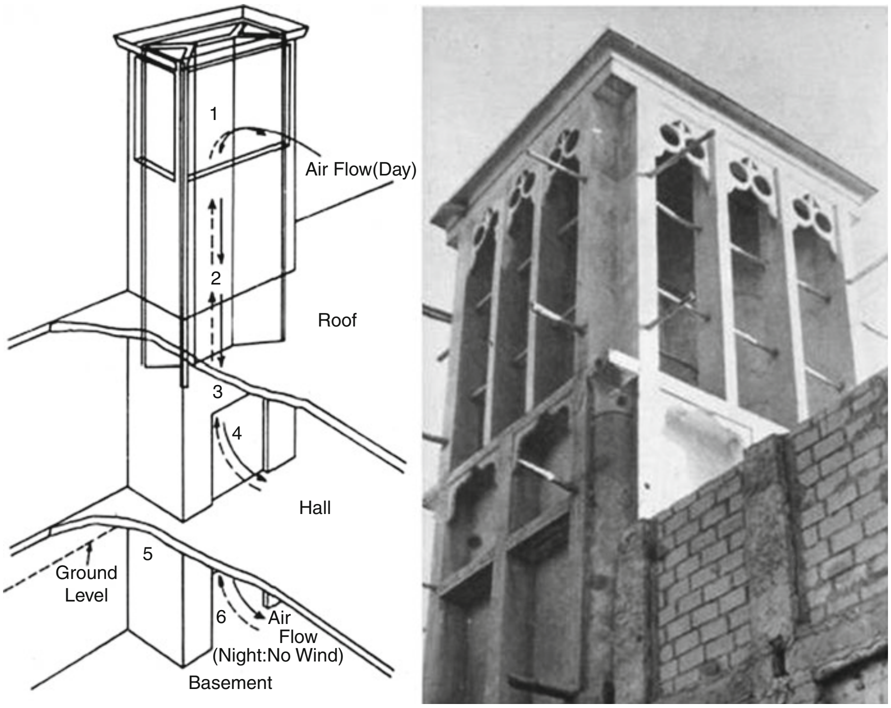
The wind towers called *bagdirs* are a distinctive and ancient feature of Islamic architecture. It has been used for centuries to create natural ventilation in buildings. Examples of wind towers (Fig. 1) can be found throughout the Middle East, Pakistan, and Afghanistan and now are sometimes incorporated into Western architecture.

Wind flowing around a building causes separation of flow which creates a positive pressure on the windward side and a negative pressure on the leeward side of the building. Due to its height the wind tower enhances the positive pressure on the windward side; it is then directed through the tower into the building. Airflow follows the pressure gradients within the structure and exits through purposely designed openings and as well as through the leeward side of the tower. The size and location of openings (e.g., windows, doors, etc.) and distribution of internal party walls have a great impact on encouraging cross flow and mixing of the indoor air.

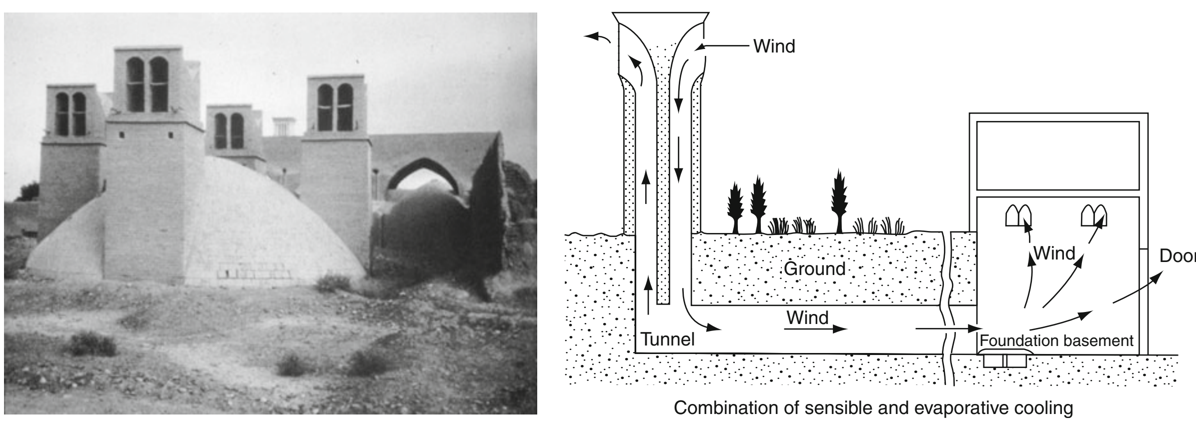
The principal factor is the buoyancy which depends on the temperature difference and the height. During the day the sun heats up the structure warming the internal air which then rises through the wind tower, as illustrated in Fig. 1. At night the cool night air lowers the temperature of the structure and the internal air and the heavier air then flows downward cooling the internal spaces after the heat of the day. Figure 2 shows how wind towers can also provide natural cooling for underground water cisterns.

Courtyards

Courtyards are one of the oldest plan forms for dwellings going back thousands of years and appearing



Natural Ventilation in Built Environment. Figure 1
Bagdir in Dubai, in United Arab Emirates [2]



Natural Ventilation in Built Environment. Figure 2
Wind towers in Yazd, Iran to ventilate houses, are also constructed to cool underground cisterns (water reservoir) [3]

as a distinctive form in many regions in the world. Examples exist in Latin America, China, the Middle East, Mediterranean, and in Europe. Preserving the basic typology of the courtyard, local climate and culture has created a unique style for each region.

The Courtyard House (Siheyuan) is a typical form in ancient Chinese architecture, especially in northern China. It offers space, comfort, quiet, and privacy. A Siheyuan consists of a rectangle with a row of houses bordering each side around a courtyard, normally with a southern orientation and having the only gate usually situated in the southeast side. Walls protect the houses from the harsh winter winds and the spring dust storms that frequently occur in Northern China from the Gobi desert in Mongolia. The house's deep eaves allow the winter sun's warmth to be directed into the rooms, while they also provide cooling shade and protection from the summer rains. Their design reflects the traditions of China, following the rules of Feng Shui and Confucian tenets of order and hierarchy.

All the rooms around the courtyard have doors and large windows facing onto the yard and small windows high up on the back wall facing out onto the street. Ridged roof tops provide shade in the summer and retain warmth in the winter. The verandah divides the courtyard into several big and small spaces that are closely connected, providing a common place for people to enjoy whatever the weather. The courtyard is an open-air living room and garden with plants, rocks, and flowers, for family members to chat and gather.

In cold northern China, courtyards are built broad and large to increase the exposure to sunlight, and there are more open areas inside the courtyard walls for daylight, fresh air, rainwater for plants and gardens to

Natural Ventilation in Built Environment. Figure 3
A typical courtyard house in southern China

be harnessed. In hot southern China, the courtyard houses (Fig. 3) are built with multiple stories to encourage cross ventilation flow incorporating natural cooling effects. The orientation of houses is not strictly north–south aligned, but follows the local topology of hills and easy access to water sources.

Lessons from Nature: Termitaries

Termites are an outstanding example in the animal kingdom of ingenious animal architects in the sense of master builders. Over 2,000 species live in tropical and subtropical regions and have shown us by analogy the art of designing for living in a variety of dwelling styles with natural ventilation.

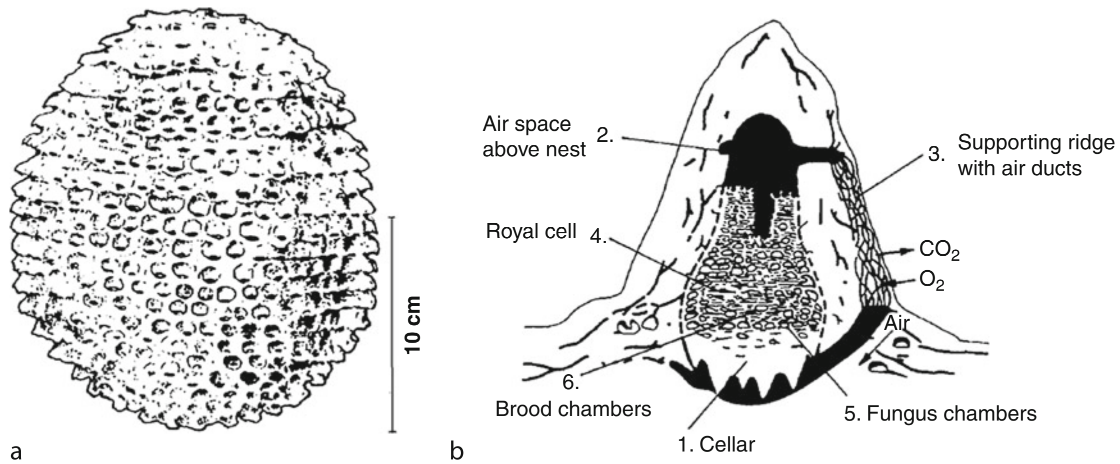
Termites build their nest so as to achieve automatic ventilation to regulate the internal temperature, as well as constantly managing control of gas exchange and moisture level. They do not keep a set temperature, but allow a gradual change between the seasons determined by the external environmental temperature.

In Australia, compass termites build large-sized mounds in the form of huge, flat chisel-shaped blades, with their long axis pointing north–south. This arrangement exposes the minimum possible area to the midday sun but allows the mounds to catch the rays of the early morning and late evening sun, when the termites need warmth, especially in the cold season; peak temperatures can be lowered by about 7°C with N–S orientation and thus maintain a preferred temperature of 30–32°C [4].

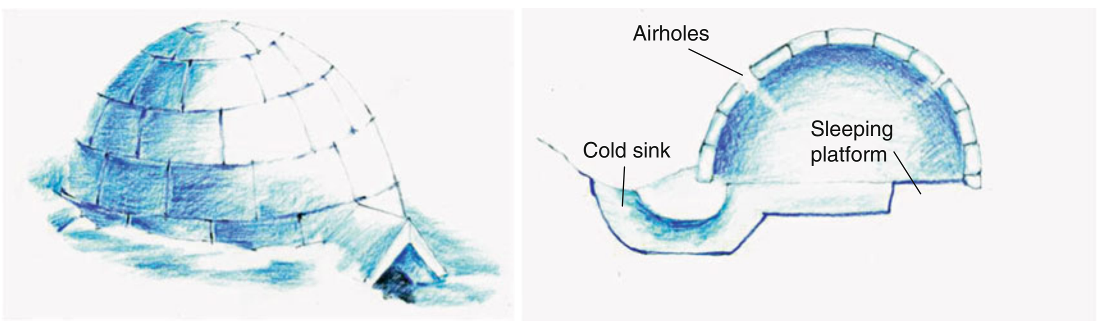
There are two main types of termite mounds: (1) The *open ventilation* mounds which let air flow into or out through chimneys or holes built into the mounds; (2) The completely *enclosed mounds* in which gases are exchanged through the porous thin-walled tunnels.

The nest of a termite species *Apicotermes gurgulifex* is shown in Fig. 4a. It is embedded in the soil but clothed by a mantle of air; the nest is constructed from the excrement of the termites so is well insulated. Its outer wall has a pattern of raised, ring-shaped configurations which surround an array of precisely spaced and shaped ventilation slits. These slits link the external and the internal spaces.

The termitary of the fungus cultivating termites, *Macrotermes bellicosus* in Fig. 4b, may reach a height of 3 or 4 m and contain more than two million termites.



Natural Ventilation in Built Environment. Figure 4
Ventilation of termite molds (**a**) Nest of a termite species *Apicotermes gurgulifex* [4]; (**b**) Longitudinal section through the nest of *Macrotermes bellicosus* from Ivory Coast showing the air being circulated by buoyancy [4]

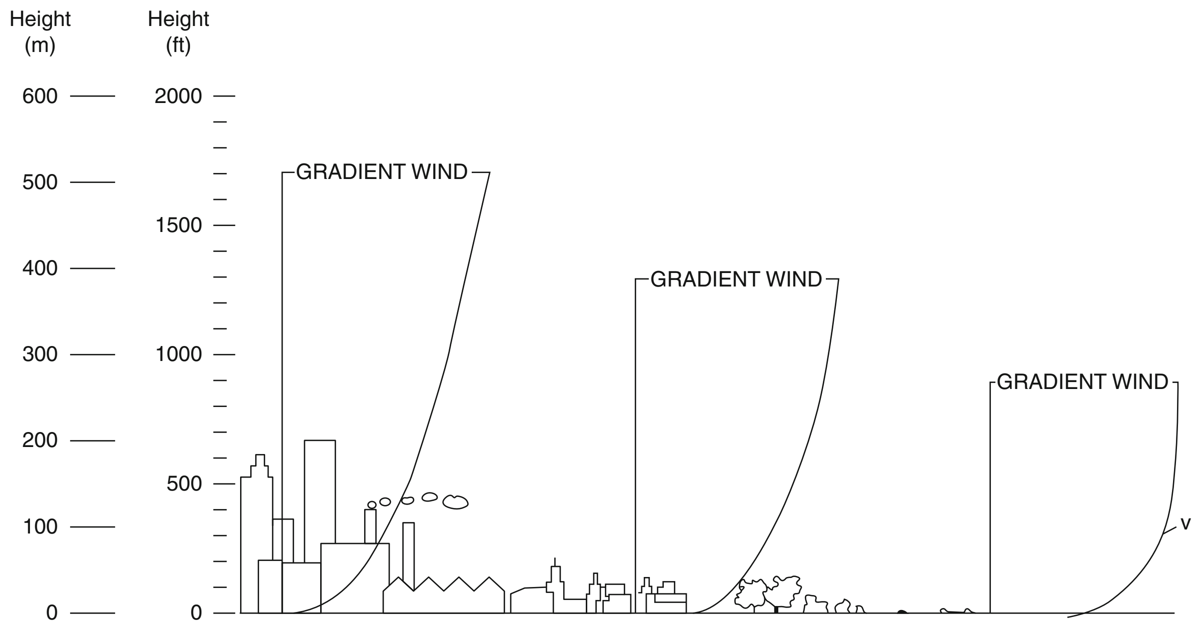


Natural Ventilation in Built Environment. Figure 5
Illustration of an igloo

The fungus chambers are built into complex sponge-like structures with numerous supporting ridges with air ducts. The air in the fungus chamber is heated by fermentation processes and the metabolic heat generated by the termites. The hot air rises and enters the duct systems in the ridges, the walls of which are porous allowing carbon dioxide to escape from and oxygen to enter the dwelling. The cooler air flows down to the cellar and replaces the rising warmer air.

Igloos

Inuit people build igloos as shelters from the extreme weather conditions in the Arctic. The igloo (Fig. 5) has an excellent thermal performance without mechanical equipment. The hemispherical shape of the igloo provides the maximum resistance to winter gales from all directions, which at the same time exposing the minimum surface area to heat loss. The dome uses packed snow blocks, some 500 mm thick, 1,000 mm long, and 150 mm wide, which are laid in a continuous in sloping pile. Effectively, the shape encloses the largest volume with the least material, so it can be heated by a blubber lamp. Coated by a glaze of ice on the interior surface, the finished dome is made stronger and windproof. The interior surface is also draped with animal skins and furs to prevent radiant and convective heat loss between the cold floor and the walls. Measurements



Natural Ventilation in Built Environment. Figure 6
Wind speed variation with height and terrain conditions [7]

have shown that with no heat source apart from the small blubber lamp, internal air temperatures are held at levels of −6 to 4°C with external temperatures of −24 and −40°C [5].

General

Traditional building technologies have evolved and been adapted over time by people and animals in all climates to meet specific needs, accommodating the values, economies, and the culture inspired ways of life. However versatile they are all reflect the basic principles described in the next section.

Natural Ventilation Principles

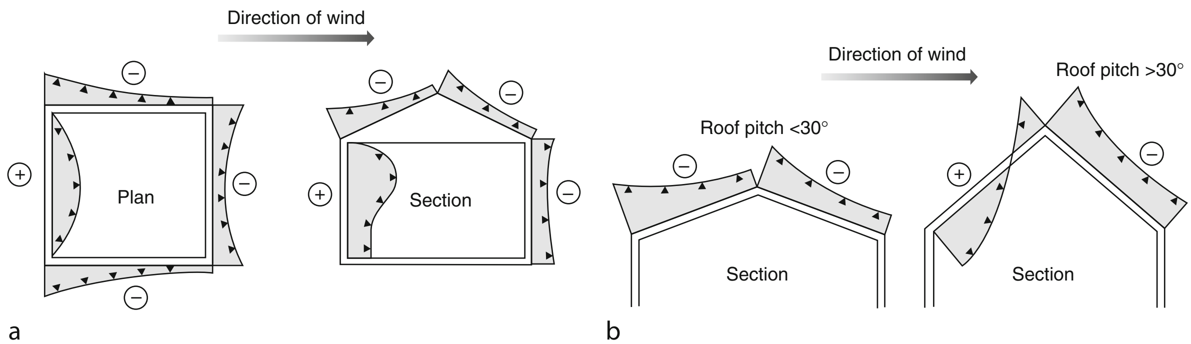
Natural forces to drive ventilation can be wind pressures or pressure generated by the density difference between indoor and outdoor air.

Wind-Driven Ventilation

Wind is caused by pressure differences in the atmosphere. The general flow of wind close to the Earth's surface is subjected to boundary layer effects, so called the atmospheric boundary layer, in which wind speed is influenced by surface friction of the ground. The variation of wind speed in height on different terrains is illustrated in Fig. 6. Wind speed correction coefficients for different terrain conditions in the UK are listed in BS 5925 [6].

When the path of the wind is checked by obstacles, such as trees and buildings, then an energy conversion takes place. Velocity pressure is converted to static pressure, so that on the windward side an overpressure is produced (about 0.5–0.8 times the wind velocity), whereas on the leeward side an under-pressure results (about 0.3–0.4 times the wind velocity). The pressure distribution on the roof varies according to pitch. Figure 7 shows areas of positive and negative pressures generated by wind normal to building front: wind-driven flow through inlets on positive pressure faces and outlets on negative pressure faces [8]. The pressure differentials arising across a building cause infiltration of air through window cracks and other openings.

Relative to the static pressure of the free wind, the pressure on any point on the surface of a building façade p_w can be approximated by the equation:



Natural Ventilation in Built Environment. Figure 7
Wind pressure distribution on buildings (**a**) Wind pressure on building; (**b**) Wind pressure on roof [8]

$$p_w = 0.5\rho C_p {v_z}^2 (P_a) \qquad (1)$$

where

C_p = Wind pressure coefficient (dimensionless)
v_z = Local wind speed at a specific reference height z (m/s)
ρ = Air density (kg/m^3)

In order to calculate the ventilation rate due to the wind a knowledge of the wind speed and direction is necessary besides information about the nature of wind-stream patterns developed around the building. Summary of façade-averaged wind pressure coefficient data for simple rectangular-plan low-rise buildings in varying degrees of shelter and wind directions is given in the *AIVC Application Guide: A Guide to Energy Efficient Ventilation* [9].

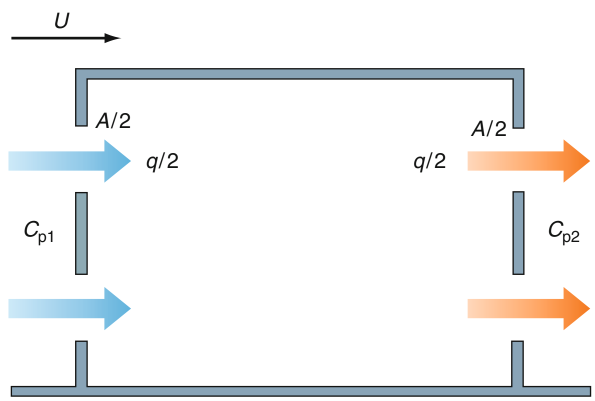
For buildings with a simple layout, the natural ventilation airflow rate by wind effect can be determined as in the following case, more examples are given in *CIBSE Applications Manual AM 10* [10]:

(a) Wind effect alone for a zone with multi cross flow openings (Fig. 8):

$$q = A \cdot C_d \cdot U \cdot \left[\frac{\Delta C_p}{2}\right]^{0.5} \qquad (2)$$

where

U is the wind speed measured at the same height as the building (m/s)
A is the total ventilation area (m^2) – assuming the four openings are identical

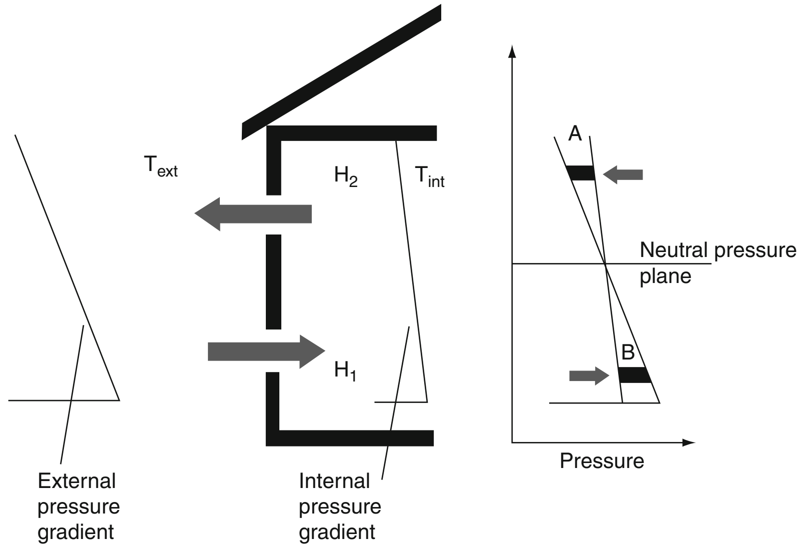


Natural Ventilation in Built Environment. Figure 8
Cross ventilation driven by wind effect alone

C_d is the discharge coefficient (typical value ~0.6)
ΔC_p is the difference between wind pressure coefficient (C_{p1} and C_{p2})

Buoyancy-Driven (Stack) Ventilation

Warm air in a room tends to rise because of its low density. It is replaced by cooler, denser air from outside. There is a neutral pressure plane where the pressure difference is zero as shown in Fig. 9. Since the pressure at the outlet or inlet can be affected by the wind, the extent to which the stack effect operates is governed partly by the wind pressure and partly by the design of the openings and the internal layout.



Natural Ventilation in Built Environment. Figure 9
Stack pressure distribution between two vertically placed openings ([9] p. 214)

For buildings with a simple layout, the natural ventilation airflow rate by buoyancy effect can be determined as in the following case [10]:

(a) Buoyancy effect alone for a single-opening zone (Fig. 10):

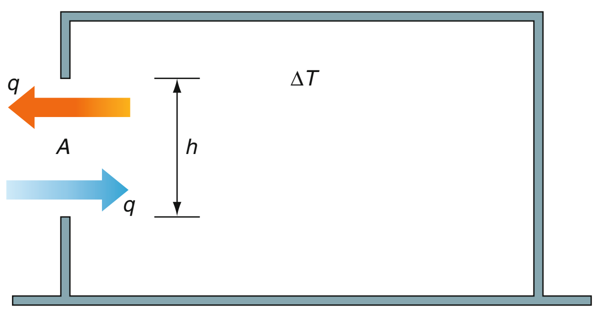
$$q = \frac{A \cdot C_d}{\left[\frac{(T_i+273)}{\Delta T \cdot g \cdot h}\right]^{0.5}} \qquad (3)$$

where

q is the ventilation flow rate (m^3/s)
T_i is the internal temperature (°C)
ΔT is the difference between the internal and external air temperature (K)
A is the opening area (m^2)
h is the opening height (m)
C_d is the discharge coefficient (~0.25 for single-opening)
g is acceleration due to gravity (m/s^2)

In spaces with high ceilings and where cross ventilation is not feasible, stack ventilation works best (Fig. 11).

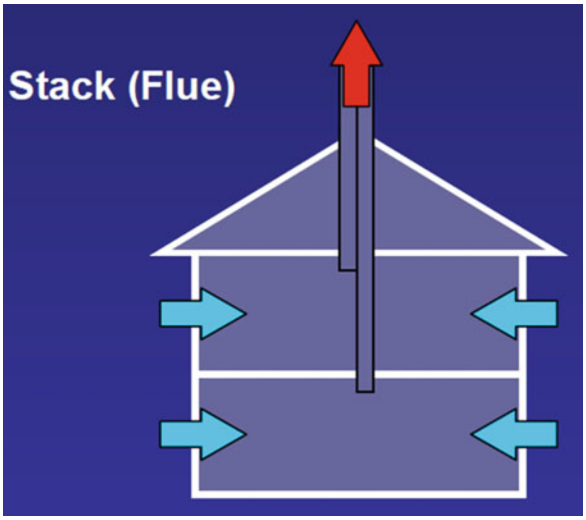
An atrium is a variant of stack ventilation principle (Fig. 12). It draws air from both sides of the building toward a central extract point, doubled the natural ventilation effective width in the building.



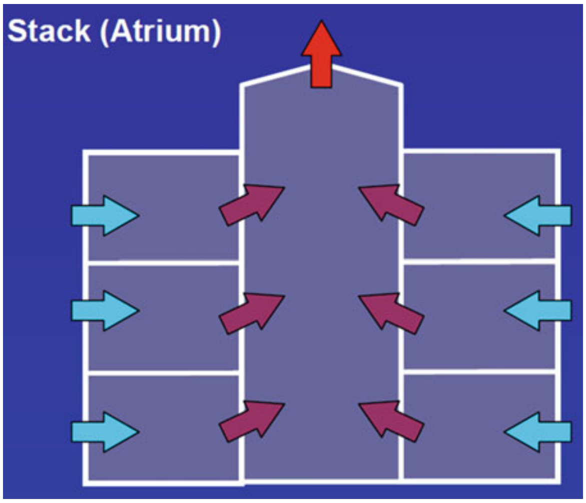
Natural Ventilation in Built Environment. Figure 10
Single-sided ventilation, single-opening, driven by buoyancy alone

A well-designed double-skin façade provides buildings with additional protective layer from outdoor environment, improves thermal and visual comfort for occupants and reduce intrusive noise. It can create the circulation and integration of the internal and external space of building, providing views to outside and so achieve the harmonious integration of people and nature.

The Gherkin building (see Fig. 13), 30 St Mary Axe in the city of London, is naturally ventilated in most time of the year, its exterior cladding consists of triangular and diamond shaped glass panels. The glazing



Natural Ventilation in Built Environment. Figure 11
Stack ventilation from vertical chimneys [11]



Natural Ventilation in Built Environment. Figure 12
Stack ventilation from Atrium [11]

system contains a double-glazed outer layer and a single-glazed inner screen with solar-control blinds in the central ventilated cavity. Fresh air is drawn up through spiraling light wells which consists of openable double-glazed panels, also effectively reduce the need for additional heating and cooling. The circular tapering shape of the building and the light wells maximized the amount of natural light throughout the building and provide views out across the City from deep inside.

When natural forces cannot provide the required indoor environment conditions, mechanical systems/components, – e.g., fans for increasing ventilation rate, and/or heat exchanger for cooling (or heating) at peak summer (or winter) times – can be used to enhance the natural ventilation through purposely installed openings in the building envelope. *Hybrid ventilation* (mixed-mode) system with pressure sensors and motor-driven dampers are used to give control. Careful considerations in the design and operation as well as end-user education are needed to deliver effective environmental control with ventilation.

Natural Ventilation Design Requirements

Fresh Air

Indoor CO_2 source is primarily generated through human metabolism. Human respiration requires a fresh air rate of 0.1–0.9 l/s per person depending on the activities (metabolic rate) and clothing insulation [14].

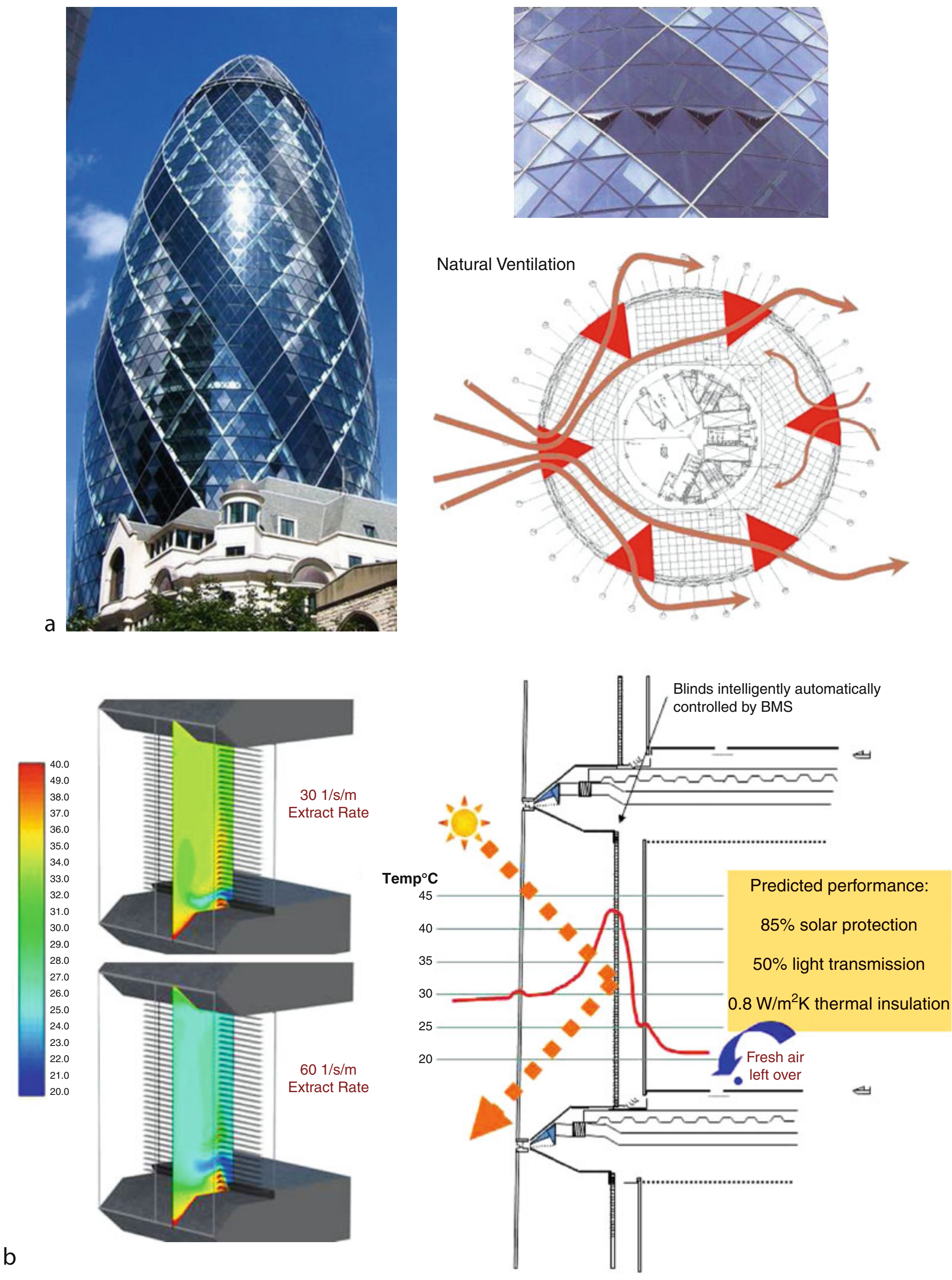
Seppänen et al. [15] and Wargocki et al. [16] have made a comprehensive review of over 20 studies with over 30,000 persons and found that ventilation rates below 10 l/s per person results in lower air quality and increase health problems.

Ventilation rates for acceptable indoor air quality are currently assessed by using the ASHRAE Standard 62.1 [17]. In this Standard there are two procedures for estimating the amount of fresh air required. The first is referred to as the ventilation rate and is a prescriptive approach stating that, for office buildings, there is a requirement of 10 l/s per person of fresh air (nonsmoking). A comparison of Standards for the indoor environment is given in the ASHRAE Handbook on Fundamentals [18].

Air Movement in Rooms

It has been well established that air movement is one of the important factors that influence people's perception of thermal comfort [19].

Air movement is a combination of a momentum-induced air flow and buoyancy-induced air flow [20].



Natural Ventilation in Built Environment. Figure 13
Gherkin London and ventilation through double-skin facade (**a**) Gherkin façade [12] and natural ventilation concept [13]; (**b**) Gherkin double-skin facade design [13]

A jet air flow is caused by a momentum source, which can either be a fan or the pressure difference across an opening caused by the wind or temperature difference. The other main source of air motion is buoyancy-driven air flow caused by density differences. This type of motion is also called natural convection.

The research work of Linke [21], Mullejans [22], and van Gunst [23] has given clear indications about the air patterns produced by air streams at various velocities and temperatures, when directed through different types of outlet, and also their interaction with the natural convection currents in the space. Optimum air and temperature distribution as well as a satisfactory sound level should be provided from the air streams outlet.

- Air movement should vary in space and time without giving drafts, especially, some parts of the body (i.e., ankles, back of the neck) are more susceptible to drafts.
- Temperatures should vary within a vertical gradient limit, higher level of warmth being preferable at below knee level rather than at head level.
- For freshness higher air velocity are required at higher temperatures, an air velocity change of 0.15 m/s being equivalent to a change of about 1°C in temperature. Air at a lower temperature and relative humidity of 40–60% (i.e., air with a lower enthalpy is perceived as fresher than air with a higher enthalpy [24, 25]).
- Above the head the convection air velocities can be 0.25 m/s or higher depending on the occupancy density and also the amount of artificial lighting.
- Air movement helps to dispel a sense of stuffiness.

Indoor Air Quality and Natural Ventilation

Body Odors A human being's sense of smell permits very low concentrations of odors. The sensitivity varies between individuals. In a typical indoors around 500 out of 6,000 compounds are human bioeffluents [26].

Poor-quality air is usually referred to as being stuffy, stale, close, heavy, or lacking in freshness. Inhaled air comes into contact with the nasal passages and then the respiratory tissue; in each case the motion of the olfactory hairs, and of the cilia on the respiratory membrane, is affected by temperature, humidity, dirt, odors, and also ions [27].

Environmental Tobacco Smoke Environmental tobacco smoke contains more than 4,000 chemicals and at least 50 of these chemicals are known cancer-causing substances [28]. It generates about 2 ppm CO, leads to irritation and discomfort among 20% of those exposed, also suspected increase in the risk of lung cancer [29]. Based on a study on the rates of hospital admissions for heart attacks before and after the smoking ban was introduced in England on July 01, 2007, there was a clear association between the smoking ban and a 2.4% reduction (or 1,200 fewer admissions due to a heart attack) in the 12 months following the ban [30].

Metabolic Carbon Dioxide An average sedentary adult (Metabolic Rate M = 70 W/m^2 and body area A = 1.8 m^2) produces approximately 0.0051 l/s (18 l/h) of CO_2 by respiration when performing light office duties [6]. Younger people such as infants and primary school children have lower emission rates but, they are likely to be more active and may well have CO_2 production at similar levels [29].

Normally, in buildings, CO_2 concentrations below 0.1% (1,000 ppm) are required to avoid discomfort and headaches [31]. According to the Canadian Center for Occupational Health and Safety [32], and also the ASHRAE standard [17], health effects can become acute at higher exposure levels.

Increased CO_2 content of the external atmosphere causes the decreased pH value of the blood [33]. Metabolism is very sensitive to body fluid pH value. Health concerns is another reason, besides global warming why the atmosphere CO_2 concentration should be limited to $<$426 ppm [27].

Volatile Organic Compounds (VOCs) Thousands of chemical compounds have been identified in the indoor environment. The most common pollutants are given in [17, 34]. Contaminants such as formaldehyde, toluene, volatile organic compounds (VOCs), allergens, and radon can accumulate in poorly ventilated buildings, causing health problems.

Complex mixtures of organic chemicals in indoor air also have the potential to invoke subtle effects on the central and peripheral nervous system, leading to changes in behavior and performance [35]. The latest overview on knowledge and research outcomes concerning the relationships between indoor air pollutants and health effects highlighted future research directions [36]:

- Development of validated measuring methods
- Establishment of dose–response relationships
- Development of risk indicators for multiple exposures

Natural Ventilation for Cooling

To obtain cooling and remove heat from internal spaces, the incoming air from surroundings must be cooler than indoor temperature. The potential sources for the cool air may be from a shaded or landscaped space or from over a body of water, a labyrinth with heavy thermal mass, underground channels, or other source of cooling.

Cross ventilation is normally the primary strategy for passive cooling. Solar chimneys can be constructed to capture solar radiation to increase the difference in temperature between incoming and out-flowing air to enhance stack ventilation. In moderate and cold climates, nighttime ventilation can be applied to passively cool the building structure and provide a heat sink during the daytime occupancy period to achieve good thermal comfort.

Openable windows, as the most commonly used vents in natural ventilation systems. There are mainly four groups windows, e.g., sliding (sash), horizontal-vane opening, vertical-vane opening, and tilt and turn windows, as illustrated in a summary table in BSRIA guide [37].

Windows selection, integrated with building form and orientation, façade details, and internal layout design contribute to create different indoor airflow patterns and provide different options for the direction and volumetric flow control. In certain conditions, i.e., local drafts, cold radiation in winter, or solar gain in summer, windows can cause localized discomfort. However, occupants of naturally ventilated buildings are generally willing to accept a wider range of internal temperature and prefer more control over their environment.

The design of traditional Mosque in Malacca, Malaysia (Fig. 14) demonstrates the combination of cross ventilation, stack or heat stratification induced ventilation to achieve cooling with natural ventilation.

Daylighting

Daylight is good for health and saving energy. Natural light has a balanced spectrum of colors and wavelengths which vary over the day depending on latitude and seasons (Fig. 15). Studies suggest that daylight has benefits over artificial light sources in regulating circadian rhythms and maintaining overall health [38].

The daylight penetration depends on the room geometry as does the air distribution. Dark colors make the space feel smaller and more enclosed, whereas lighter colors have the opposite effect. In order to create stimulating high quality interior environments, lighting design must consider source intensities, distribution, glare, color rendering, and surface modeling [39]. Improved daylight metrics can be applied in a practical, real-world context to take into account for the temporal and spatial aspects of daylight, as well as meeting design standards for energy and occupants comfort [40].

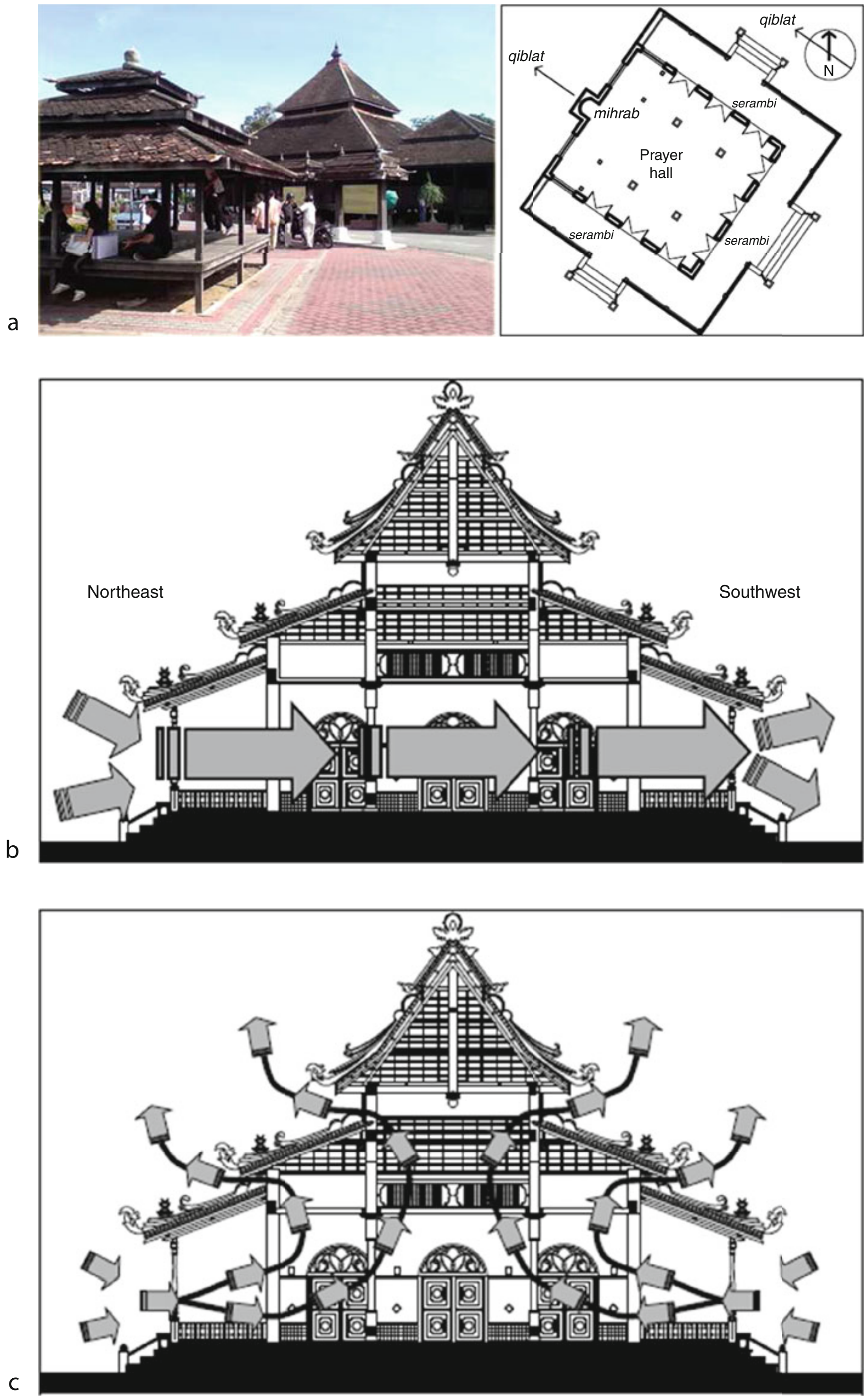
Urban Pollution, Noise, and Natural Ventilation

In the build-up urban environment, buildings and roads make up the basic geometric form of street canyons. Similar to a natural canyon, which is a steep gorge with very high sides and a minimal valley floor, an urban canyon has narrow street space bordered by very high buildings. Example of an urban canyon is the Magnificent Mile in Chicago as shown in the picture (Fig. 16).

An urban boundary layer rises above the canopy (see Fig. 17). The potential for natural ventilation is seriously affected by the reduction of wind speed, complicated turbulent dispersion patterns, elevated day- and nighttime ambient temperatures due to the urban heat island effect and increased external pollutants as well as noise level.

Based on neural network methodologies, an algorithm calculating the optimum sizes of openings for naturally ventilated buildings located in urban canyons for single-sided and stack-effect configurations was derived by Ghiaus and Allard [43].

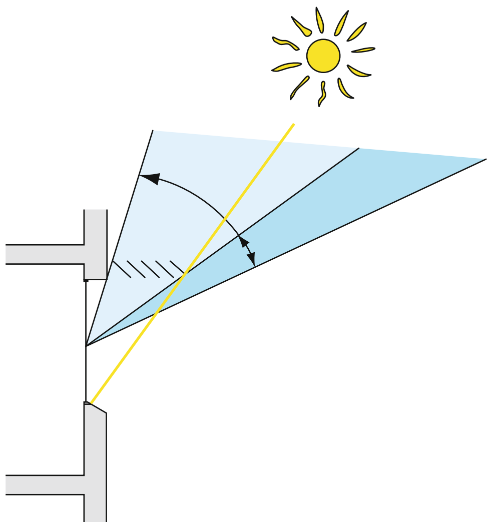
Mitigation of the urban heat island effect can be accomplished through the use of green roofs and the use of lighter-colored surfaces in urban areas, which reflect more sunlight and absorb less heat. Green roofs protect the roof materials from intense solar radiation



Natural Ventilation in Built Environment. Figure 14
Natural cooling in traditional Malacca Mosque, Malaysia [*Source*: Professor Vivian Loftness at Carnegie Mellon University] (**a**) A traditional Malacca Mosque in Malaysia and typical floor plan; (**b**) Cross ventilation design analysis, viewing toward Southeast facade; (**c**) Stack-effect design analysis

and prolong the service life time. Plants retain and absorb rain improve the microclimate and also reduce the runoff water to drainage systems.

Close to nature, even in urban settings has been long-term inspiration and challenge for architects and engineers. In Japan, Osaka Gas Corporation sponsored an experimental "Open Building" (Fig. 18) project NEXT21 since 1994. The structural and building services have same basic units using resources more effectively through systemized construction [44]. A variety of residential units have been designed by different architects' practices to accommodate varying households. Substantial natural greenery was planted on the "3D streets" formed by different levels of building service pathways connecting different apartments in a high-rise structure. Energy efficient measures included fuel cells and also encouraging occupants to become more aware of how to lead a comfortable life possible without increasing energy consumption.

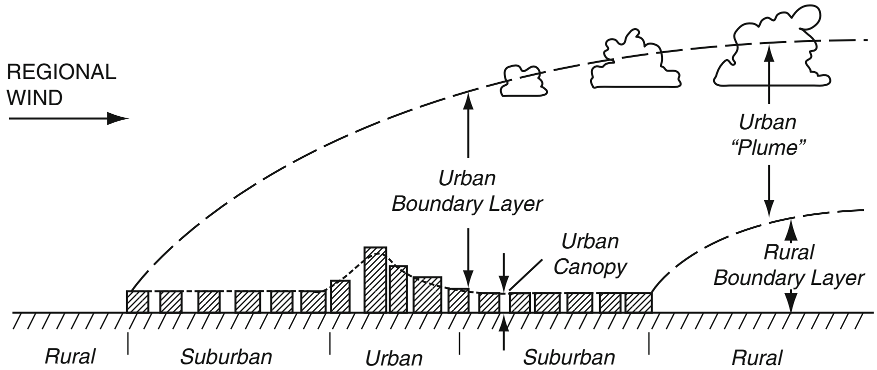


Natural Ventilation in Built Environment. Figure 15
Design to maximize daylight throughout the year [39]

An early study in climate chamber revealed that a change of 2.4 decipol in the PAQ or a change of 3.9 dB in the noise level has the same effect on thermal comfort as 1°C change in the operative temperature [46]. Recently, a number of newly built schools in the UK with different ventilation strategies have shown that the complex interaction between thermal comfort, ventilation, and acoustics are major challenges for designers [47].

The shape of the room and finishing materials of the surfaces affect the sound distribution. For example,

Natural Ventilation in Built Environment. Figure 16
Urban canyon – the magnificent Mile in Chicago [41]



Natural Ventilation in Built Environment. Figure 17
Cross-section of the urban atmosphere [42]

Natural Ventilation in Built Environment. Figure 18
Open building in Japan [45]

concert halls are densely occupied and for music demand high spaces with volumes of 10 m^3 per person. The optimum balance of direct and indirect sound depends on the shape of the space and the boundary surface sound absorption. Combined acoustic and airflow design chart and equations could help designers to achieve both adequate acoustical insulation and airflow rates requirement, especially in the early stages of the design process [48]. The newly completed broadcast center in London has showcased all kinds of sustainable technologies to achieve the world's first naturally ventilated television studios (see detailed in case study).

Humidity and Condensation Management with Natural Ventilation

Ventilation Effectiveness Ventilation effectiveness is an indicator of how efficiently supplied fresh air is mixed and distributed in the occupied space, it related to both the dilution and removal of indoor airborne contaminants [49]. Gan [50] used air flow pattern, air temperature, and local mean age of air (i.e., the average time for air to travel from an inlet to any point in a room and is equal to the room volume divided by the air supply rate) to determine the effective depth of fresh air distribution in a naturally ventilated space. CFD predictions showed that the width and height of window opening, room heat gains, and outdoor air temperature have combined effects in determining the maximum room depth for effective fresh air distribution in single-sided natural ventilation. For summer cooling requirement, thermal comfort is the determine factor compared to indoor air quality. Different from passive contaminants concentration based effectiveness measures [20], Coffey and Hunt [51] proposed three measures of ventilation effectiveness based on the active buoyancy (e.g., the heat or coolth) removal applied on natural displacement and natural mixing flows within a space.

Practical design guidance for naturally ventilated performing arts buildings in an urban context has been outlined in Short and Cook (2005) [52]. Specific space features and operating requirements in designing auditoria were addressed and demonstrated through the presentation of three case studies. The additional technical challenges compared to common natural ventilation space design include:

- Sizing large inlet and outlet areas
- Managing acoustic attenuation
- Configuring building management system to cater for all levels of occupancy density
- Ensuring the stratification of warm, stale air forms above the breathing zone in theaters with raked seating
- Avoiding airflow imbalance generated by wind pressure

In hospital environment, natural ventilation system design need to pay special attention to eliminate the spread of biological (i.e., fungi, bacteria, and virus), chemical, and other contaminants effectively [53].

Humidity and Condensation Prevention Low ventilation rates may lead to high indoor relative humidity. Penetration of rainwater or snowmelt into the building envelope can also cause moisture accumulation into building structures or materials. Damp structures can lead to mold formation and indoor air contamination which has been shown to be strongly associated with adverse health outcomes [54].

Low ventilation rates and moisture accumulation may lead to increased dust mites in residential dwellings; the house dust mite allergen causes asthma. Mold is also associated with exacerbation of asthma and upper respiratory disease in both children and adults [3]. In Nordic residential buildings, monitoring data has shown health risk for the residents with ventilation rates below 0.5 ACH.

Studies of ventilation rate and health effects in public buildings [55] indicate that ventilation rates below 10 l/s per person have significantly associated with health risks and PAQ complaints, increased ventilation rate between 10 and ~20 l/s per person reduce sick building syndromes (SBS) and improve PAQ.

A relative humidity range of 40–60% is generally acceptable. High humidities over 60% gradually increase the risk of mold growth, and other fungal contamination, which may cause allergy and malodors. Increased humidity may also enhance other emissions in buildings, e.g., formaldehyde from furnishings [56]. A low humidity (<30%) may cause dryness and irritation of skin, eyes, and airways of some occupants [29] leading to increased throat infections. Contact lens wearers often experience discomfort in dry environments.

Correct selection of insulation materials in modern more air tight buildings will help to develop low energy buildings in refurbishment and new design but it is important to incorporate ventilation means such as trickle ventilators for example.

Fire Safety

In the event of a fire, smoke can follow natural ventilation paths, natural ventilation system must integrate fire safety strategy and provide solution which facilitates safe occupancy, escape or increased visibility for the fire service [6]. Smoke ventilation designs utilize the buoyancy of hot smoke, operates by opening automatic opening vents (AOVs) on the fire floor in conjunction with an AOV at the top of the smoke ventilation system to naturally extract smoke from the common escape routes. Depending on the building envelope and structures AOVs should be placed in natural/mechanical smoke shaft, atria, internal glazed screen/façade, escape stair/fire fighting stair, or external wall to achieve the prime objective of keeping common escape routes clear of smoke. Stand by fans should be installed as an emergency safety precaution.

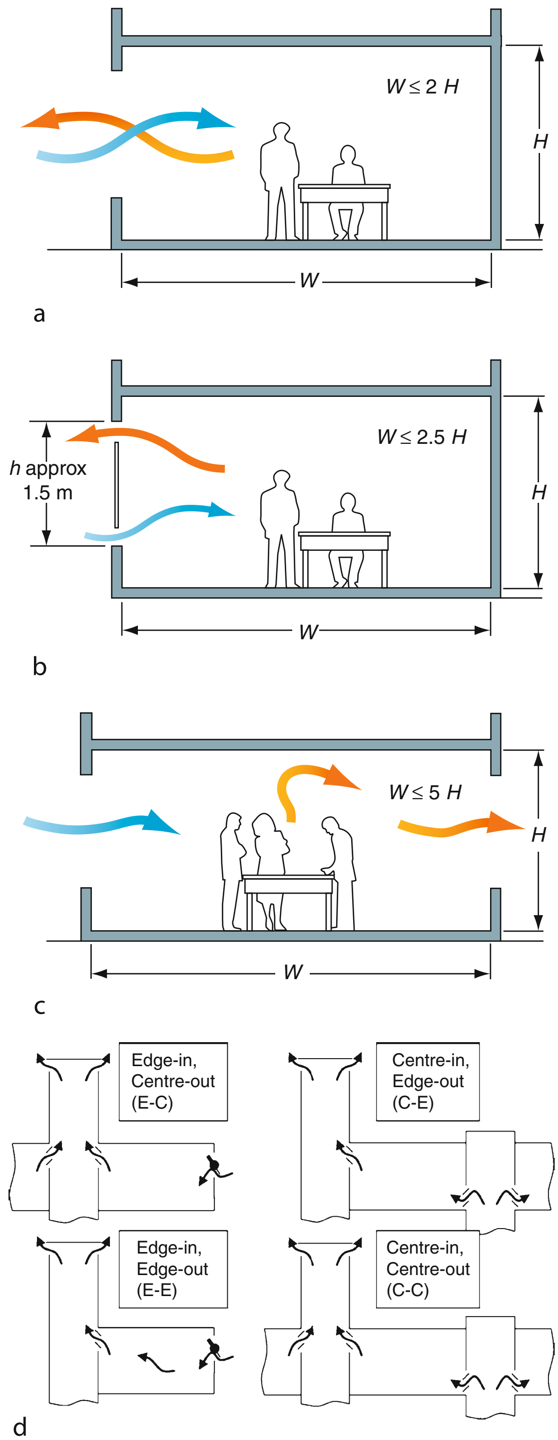
Design Guidelines

The rules of thumb for natural ventilation to be effective are as follows [10]:

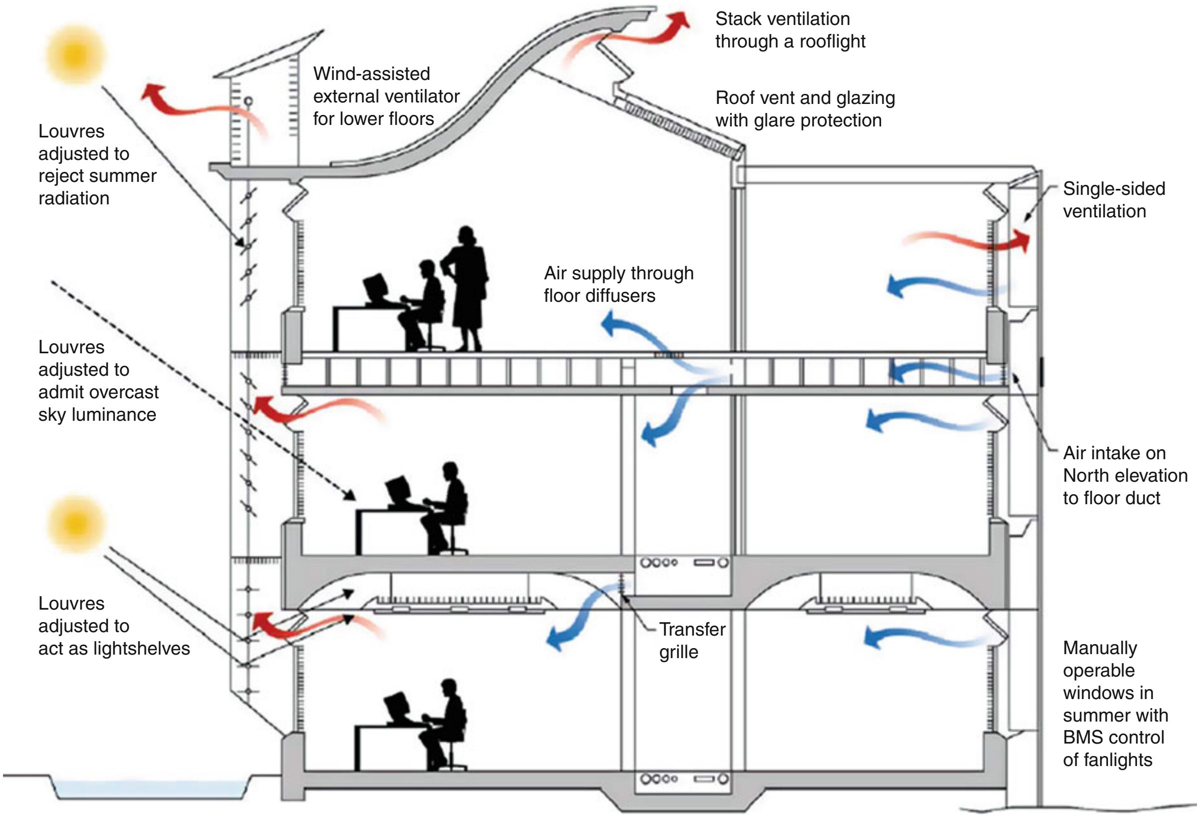
- Single-sided single-opening (mainly driven by wind turbulence) effective up to a depth of two times the floor-to-ceiling height, typically 4–6 m (Fig. 19a).
- Single-sided double-opening (mainly driven by buoyancy forces) effective up to a depth of 2.5 times the floor-to-ceiling height, typically 7–8 m (Fig. 19b).
- Cross ventilation with ventilation openings on both sides, generally opposite sides, of a space (mainly driven by wind driven) effective up to a depth of five times of the floor-to-ceiling height, typically 15 m (Fig. 19c).
- Stack ventilation is mainly driven by temperature differences between the hot air in the occupied space and the cooler external air. The effective depth of stack ventilation is up to five times of floor-to-ceiling height. Stack ventilation can also be enhanced by wind effect or through the use of a solar chimney, i.e., solar driven stack ventilation [57].
- Different forms of atrium ventilation are illustrated in Fig. 19d [58].

Figure 20 illustrates various natural ventilation strategies can be integrated into design.

For natural ventilation aim for a heat gain less than 35 W/m^2 to avoid excessive overheating. This means there is a need to reduce internal gains; ensure effective ventilation; select suitable facades and materials. Also provide CO_2 monitors to help occupants know when it is preferable to increase ventilation.



Natural Ventilation in Built Environment. Figure 19 Schematic diagrams of the different forms of natural ventilation (**a**) single-sided single-opening; (**b**) single-sided double-opening; (**c**) cross ventilation (**d**) Atrium ventilation [58]



Natural Ventilation in Built Environment. Figure 20
Illustration of various natural ventilation strategies [37]

Passive cooling can be achieved by using:

- Local climate characteristics such as breezes
- Intelligent facades
- Solar protection
- Low energy lighting
- Thermal mass
- Ventilation
- Cloud computing, which can reduce computer heat gains considerably

Evaporative down draft cooling technique [59, 60] involves introducing fresh ambient air at the top of a central lightwell and cooling it so that it flows downward, filling the space with a static reservoir of denser, cooler air.

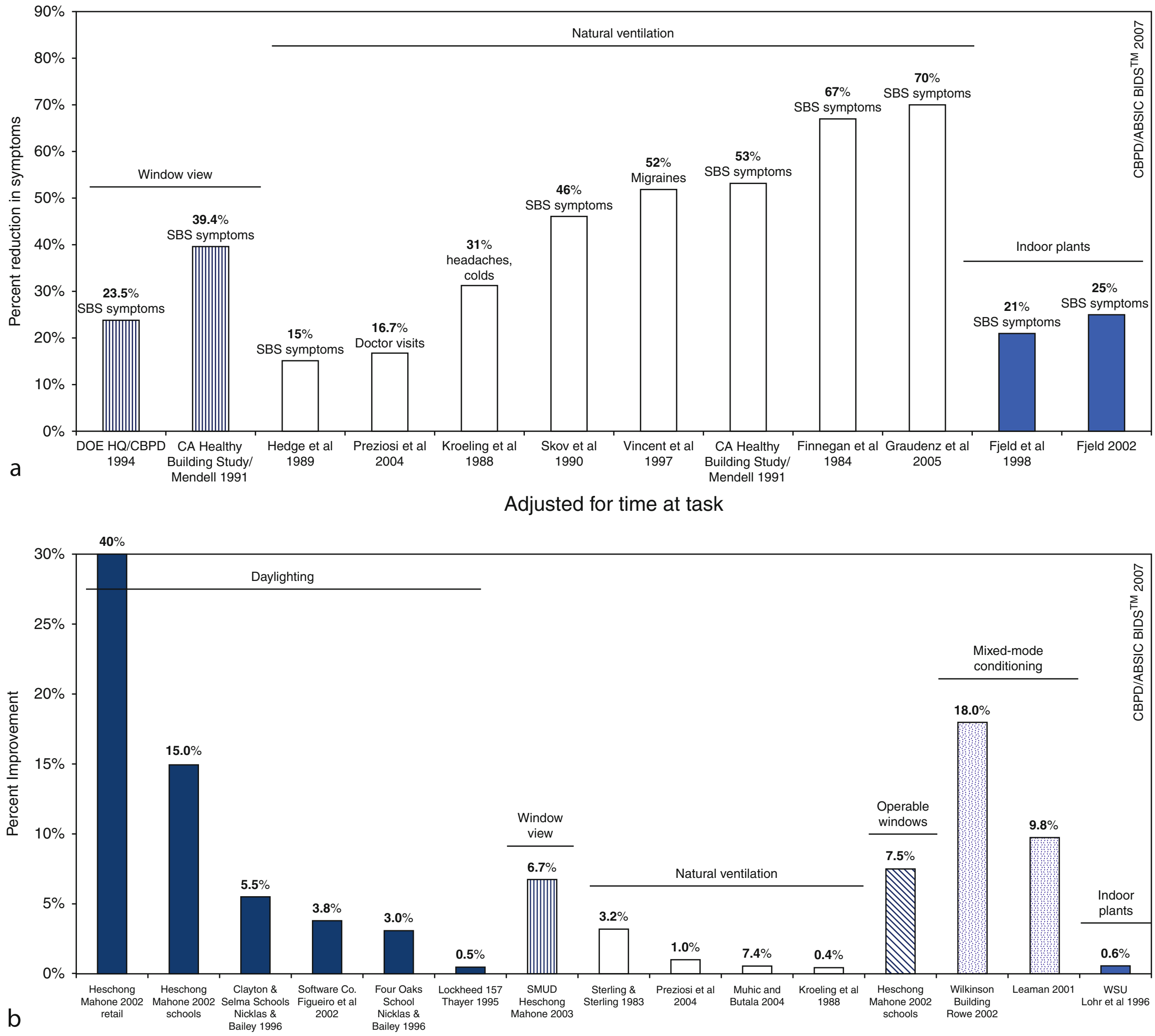
Benefits of Natural Ventilation

The parameters which affect the air velocity and temperature at a given point in the room are as follows:

1. Air inlet velocity; sound emission must also be accounted for when selecting a value for this
2. Supply to room temperature differential
3. Geometry and position of air supply outlet
4. Position of air extract outlet
5. Room geometry
6. Room surface temperatures; low surface temperature components, such as glass, tend to promote strong convection currents
7. Position, shape distribution, and emission of heat sources (e.g., people)
8. Room turbulence

The advantages of natural ventilation arise because there are no mechanical systems hence:

- Less energy is consumed
- Less plant room space is needed
- Higher level of daylight if well-designed
- Maintenance is simpler



Natural Ventilation in Built Environment. Figure 21
Health and productivity gains from access to the natural environment [61] (**a**) Health gains from access to the natural environment; (**b**) Productivity gains from access to the natural environment

- Increased durability
- No noise
- Good occupant control using windows
- Low cost

The disadvantages are as follows:

- There is no filtration or control of moisture content.
- The driving pressure depends on the wind and/or the stack effect and both are variable and cannot be easily be controlled.
- There has to be an integrated approach to design between the architect and the engineer with regards to built form; orientation; massing; internal layout; selection of window types and their positioning in the façade.
- Internal heat gains are limited to less than 35 W/m^2.

The ventilation rate depends on the strength and direction of wind and/or buoyancy forces and the resistance of the flow path. The uncontrollable feature of natural ventilation can result in the air change rate varying significantly and being distributed unevenly to internal spaces giving periods of inadequate ventilation, or periods of over ventilation and excessive energy waste.

Health and Productivity

There is a unique relationship between an individual, the environment, and the building they inhabit. The complicated interaction between the "hard" environmental stimuli, such as air and surface temperatures, humidity, air movement, and air purity, and the "soft" interlinked social and psychological factors of individuals and their organization, influences the sense of well-being, consequently the productivity. Task performance is best when the mind is alert at an optimum arousal level with the least distraction [27].

Loftness [61] shows the impact of natural ventilation on health and productivity in the Fig. 18a and b. In addition to the health and productivity benefits brought by design with access to the natural environment, effective daylighting can yield 10–60% reductions in annual lighting energy consumption. There is evidence of potential 40–75% reductions for cooling energy consumption when natural ventilation is interactively supported by mixed-mode HVAC systems.

Sustainable and healthy built environments result from integrating the natural diversity of the region – its unique climate and seasons, textures, sounds, smells, and variety of landscape and species.

Selection of Ventilation Strategies

The CIBSE AM 10 1997 [62] gives the following monograph (Fig. 22) to help the decision process for selecting whether to use natural ventilation, mechanical systems, or air-conditioning.

Design Elements for Natural Ventilation

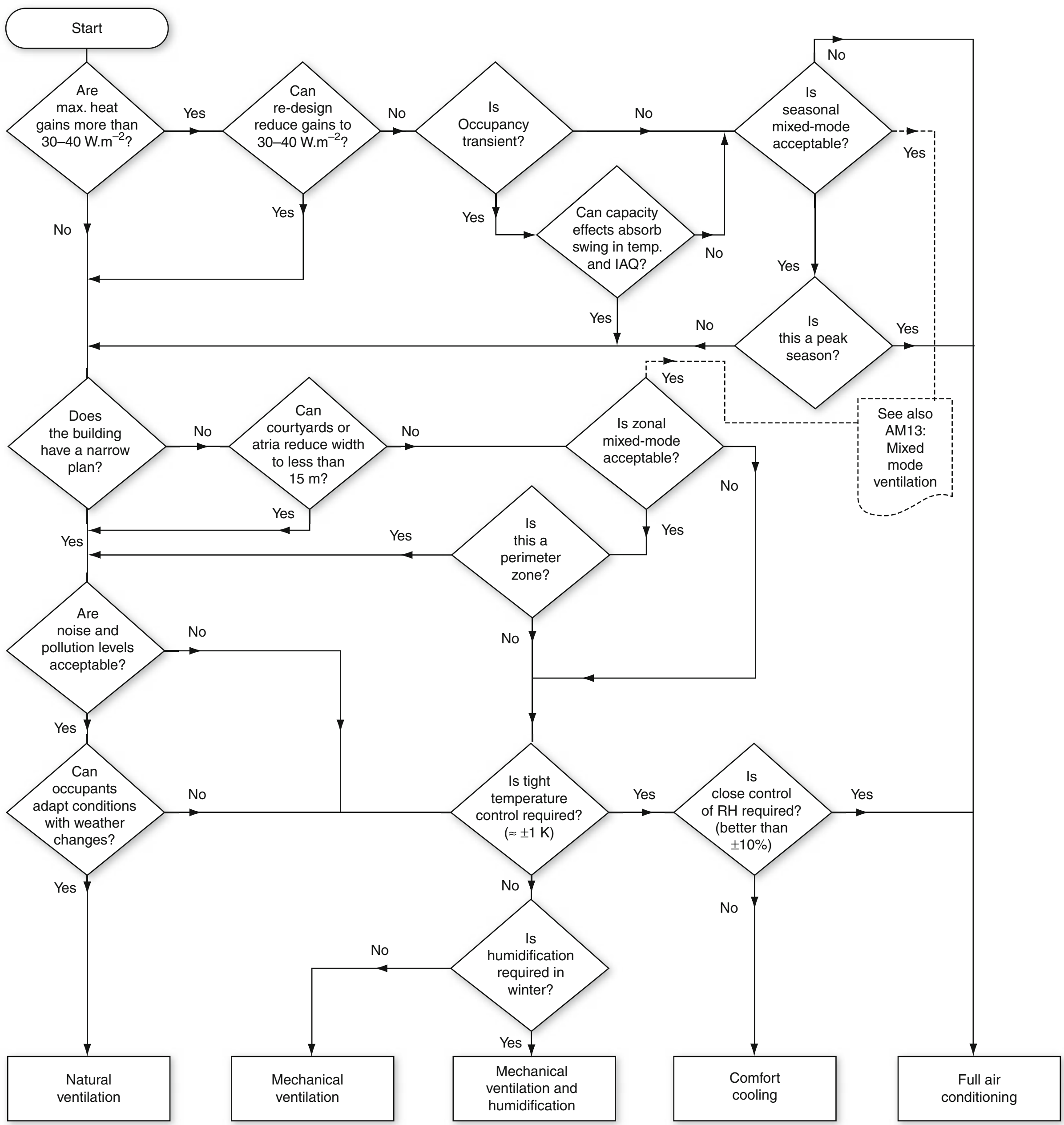
Natural ventilation can be difficult to control due to the fluctuating indoor and outdoor conditions. As previously stated naturally ventilated buildings have to be inextricably linked to architectural form and fabric; they require holistic design and significant attention to detail.

Well-designed natural ventilation systems need to address the following aspects comprehensively [62–64]:

- *Site design* – building location, orientation, site layout, and landscaping
- *Building design* – building type and function, building form and orientation, envelope, thermal mass, natural ventilation strategy, internal spatial division and functions, internal heat load, solar shading, daylight, passive night cooling potential
- *Vent opening design* – position of openings, clear path of airflow, types of openings, sizing and choice of window opening design, effective area of multiple openings, provision of secure, operable openings, and control strategy

Computer Aided Prediction Models

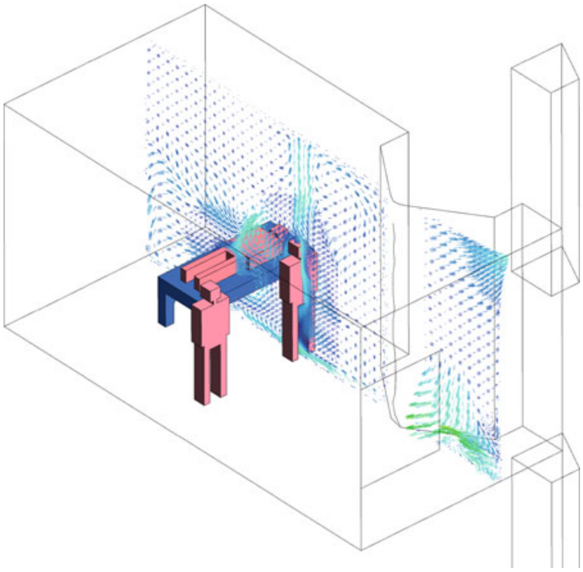
Chen [65] presented an overview of ventilation performance prediction methods, including analytical models, empirical models, small-scale experimental models, full-scale experimental models, multizone network models, zonal models and Computational Fluid Dynamics (CFD) models. Recent applications of the above simulation tools were also examined in terms of contributions for practical design and research purposes. CFD applications in modeling of wind-driven natural ventilation [66] have shown improved prediction capability for complex naturally ventilated buildings. Walker [67] developed a methodology to evaluate natural ventilation in a multizoned commercial office building by full-scale building monitoring, reduced-scale physical experiment and CFD simulation. Detailed human thermal sensation and comfort models provide more accurate predictions on the dynamics responses of occupants to building environments, also advanced coupling simulation system extends the prediction capability of CFD and brings the human occupancy factor further into the core activities of the design process of buildings [68, 69]. The integration of CFD with dynamic building simulation (BS) models and Geographic information systems (GIS) data would be a practical way to take advantage of the strength of the other models for optimal natural ventilation design and analysis. Figure 23 illustrates CFD application on advanced natural ventilation design in hospital. Lomas and Ji [70] evaluated simple natural ventilation



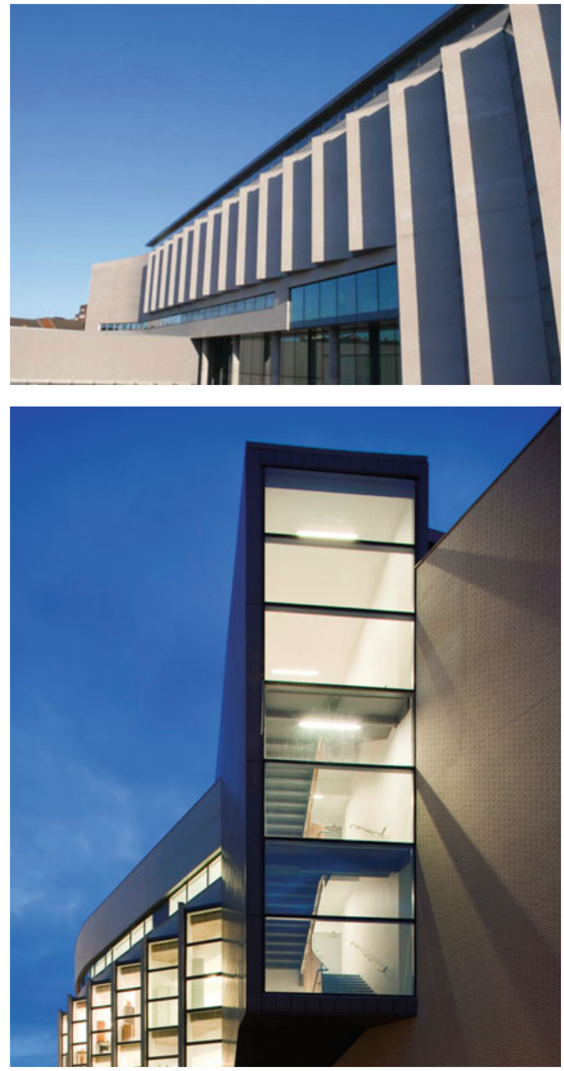
Natural Ventilation in Built Environment. Figure 22
Flowchart for selecting a ventilation strategy [62]

(SNV) and advanced natural ventilation (ANV) design in terms of overheating risk in the current and future climate in health care buildings. They also proposed an overheating risk criterion compatible with adaptive thermal comfort assessment. Both field monitoring and modeling studies showed that ANV could offer greater resilience to climate change than SNV, particularly as a refurbishment strategy.

The strengths and weaknesses of a wide range design simulation tools are summarized by



Natural Ventilation in Built Environment. Figure 23 Advanced natural ventilation system design in hospital using CFD [45]



a

b

Natural Ventilation in Built Environment. Figure 24 LJMU Liverpool façade in nighttime (**a**) LJMU Liverpool exterior; (**b**) LJMU Liverpool façade in nighttime (*Source*: Rick Mather Architects)

governmental and professional organizations [71, 72]. Educational resources and practical equations for various design stages and step-by-step guided case studies [58, 73–75] would help multidisciplinary professions to design and build sustainable buildings.

The following case studies showcase innovative solution to natural and mixed-mode ventilated buildings in the built environment.

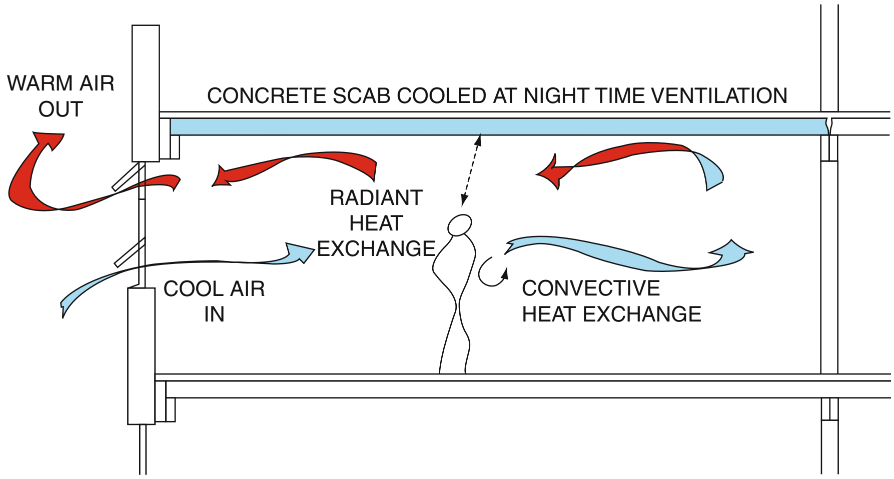
Case Studies

Case Study 1: Liverpool John Moores University, UK

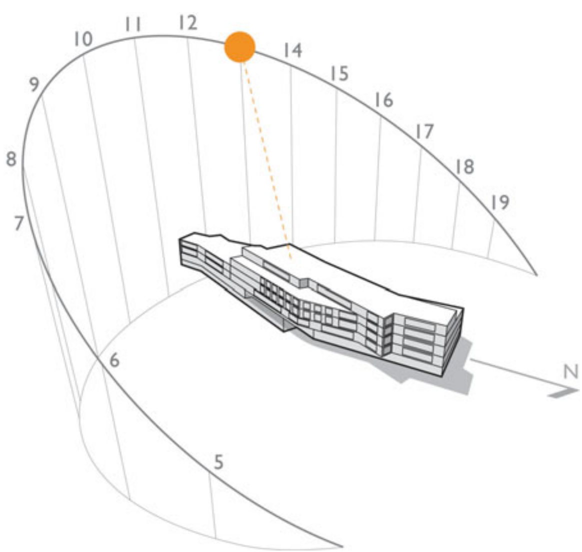
The Liverpool John Moores University art and design academy was designed by award winning Rick Mather Architects and engineered by Whitbybird Engineers and was built by Wates Construction. The building was designed from 2004 and opened in 2008 (see Fig. 24).

The 11,000 m^2 five story university academy building had a number of important environmental initiatives on the client brief including a 25% betterment of UK conservation of fuel and power building regulations; a BREEAM target of Very Good, and a 10% onsite renewable energy target.

To meet these requirements the design team reviewed a number of architectural and structural and services engineering options and concluded that a mixed-mode ventilation scheme utilizing thermal mass with Heat Recovery would of particular benefit to a low energy approach. The building design team used the latest computer modeling techniques to prove compliance with industry standards for thermal comfort particularly the prevention of overheating (see Figs. 25, 26, 27, and 28).



Natural Ventilation in Built Environment. Figure 25
Exposed concrete soffit for thermal mass benefit



Natural Ventilation in Built Environment. Figure 26
Sun path analysis for external façade design (*Source*: Whitbybird Engineers)

The building benefits from a heavyweight thermal mass during the spring and summer, utilizes single-sided natural ventilation with mechanical extract during peak summer with nighttime free cooling (see Fig. 25), and during winter operates as a sealed building with heating provided by a biomass pellet boiler. A weather station provides data to the BEMS to ensure the automated windows are aligned with the ventilation strategy.

The building was shortlisted for various awards in 2010.

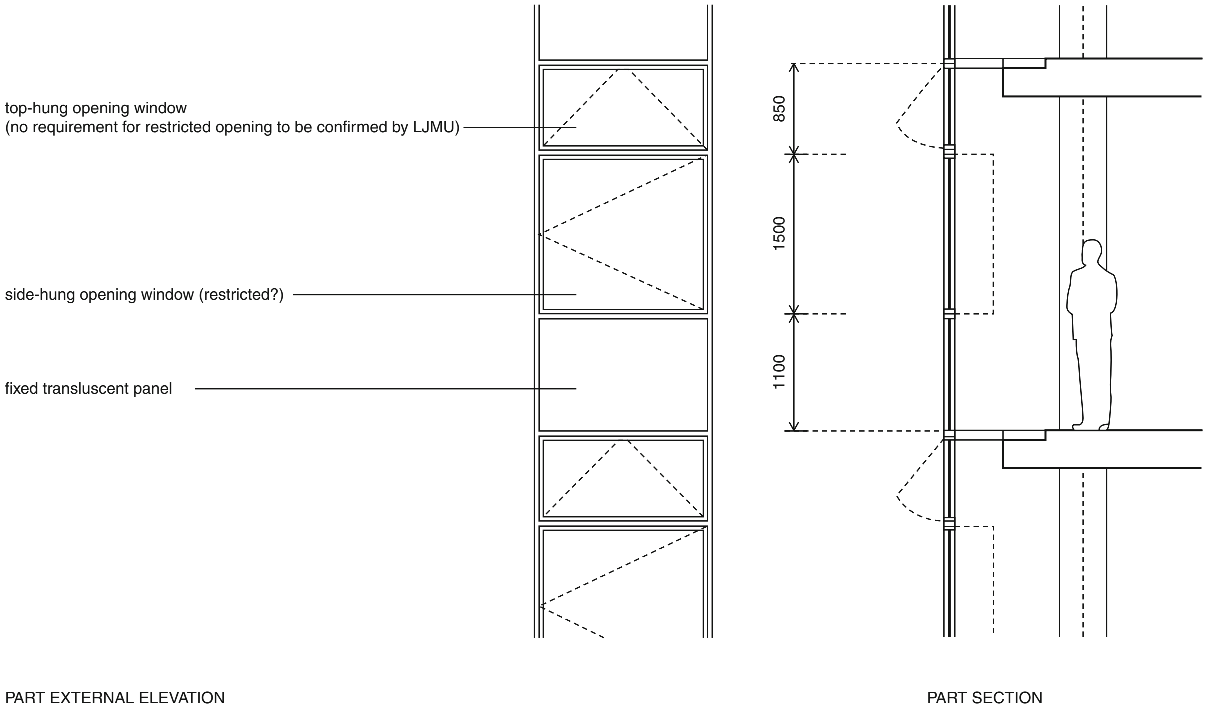
Case Study 2: Tamworth Academies – Staffordshire, UK

Two secondary school academies were commissioned by Tamworth County Council in 2009. Designed by Aedas architects and engineered by WSP and CTM the buildings were designed in 2009/2010 and are scheduled to open in 2010. Main contractors are Wilmott Dixon Construction.

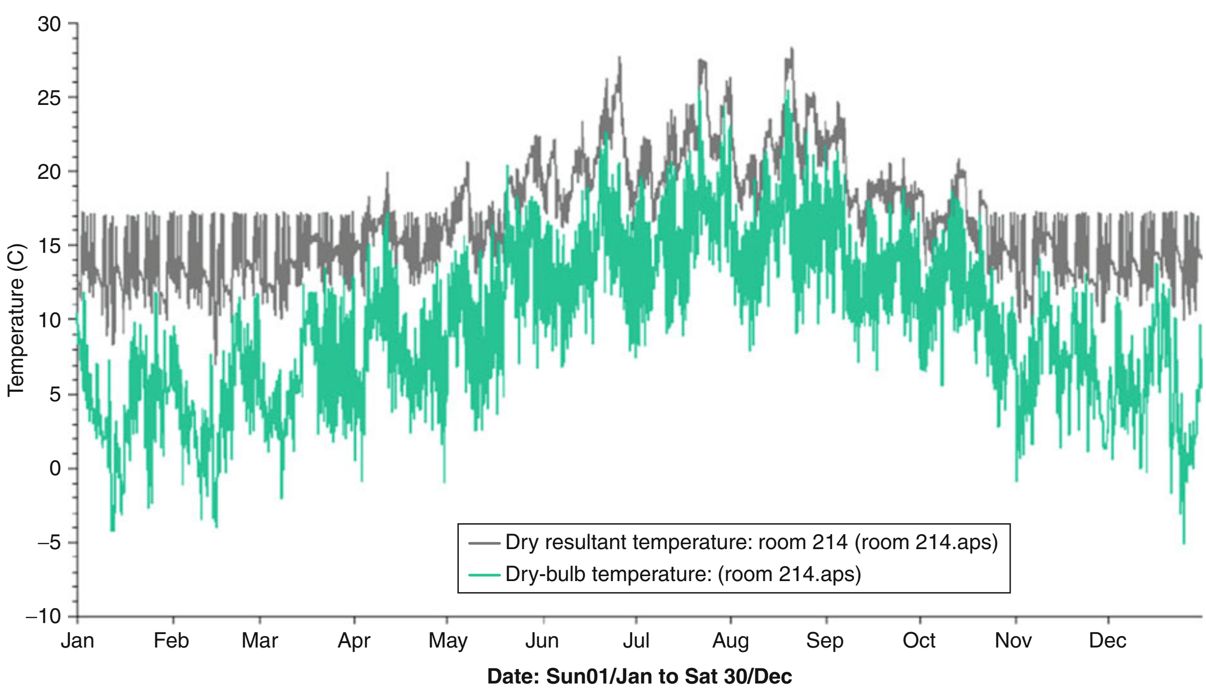
The two 9,000 m^2 two story buildings (Fig. 29) had to comply with the government's 60% carbon reduction target compared to 2002 UK building regulations. The design team also set a BREEAM environmental target of Excellent.

It was the aim of the architectural and structural and services engineering teams to strive to design a low energy building to ensure the building was future proofed against rising energy costs. In addition the client team wanted a low whole life cost solution.

The selected structural and services strategy was a building that would be designed to operate as a naturally ventilated building but be capable of

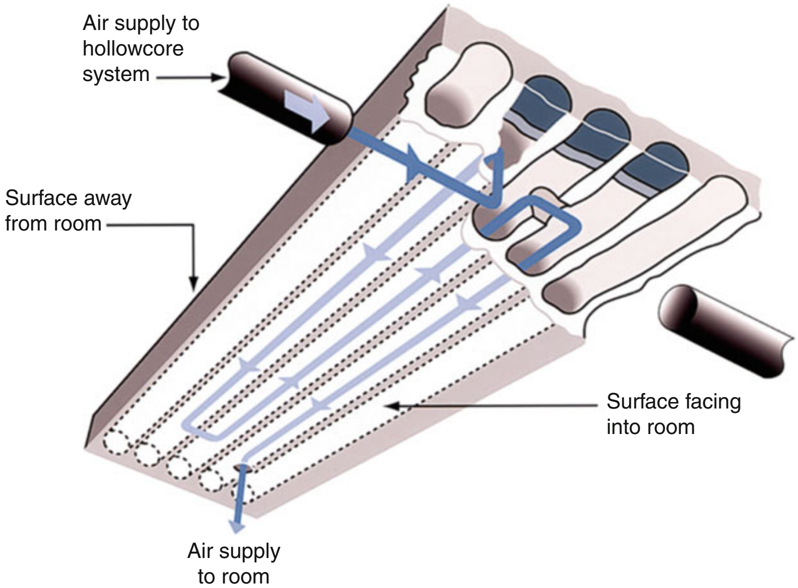


Natural Ventilation in Built Environment. Figure 27
External façade design (*Source*: Rick Mather Architects)



Natural Ventilation in Built Environment. Figure 28
Thermal modeling chart (*Source*: Whitbybird Engineers)

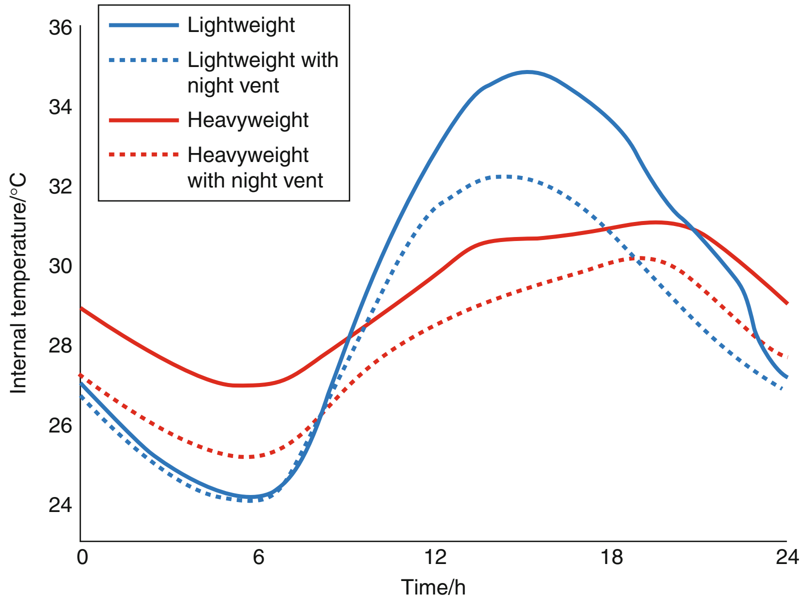
Natural Ventilation in Built Environment. Figure 29
Tamworth landau forte exterior (*Source*: Professor Vivian Loftness at Carnegie Mellon University)



Natural Ventilation in Built Environment. Figure 30
Termodeck concrete plank (*Source*: Tarmac Termodeck)

operating as a highly efficient mechanically ventilated building during peak summer and extremely cold winters to conserve energy. The client, main contractor, and design team chose Termodeck by Tarmac, an integrated structural mixed-mode ventilation scheme utilizing thermal mass free cooling with energy efficient heat recovery (see Figs. 30 and 31).

Other features of the buildings include areas of the academies where ICT gains are increased provided with chilled water generated by a ground source heat pump. And seasonal operation of the ventilation strategy communicated to the occupants of the academies via building weather station data and LCD flat screen TVs.



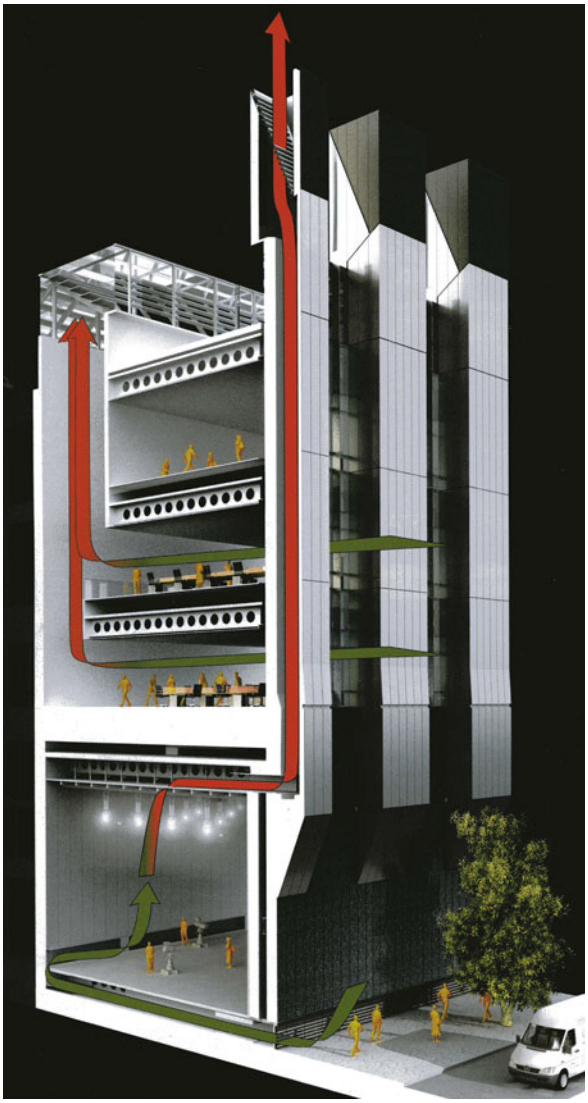
Natural Ventilation in Built Environment. Figure 31
Temperature time-lag for lightweight and heavyweight buildings (*Source*: Tarmac Termodeck)

Case Study 3: BSkyB Broadcast Center – London, UK

Designed by Arup Associates, the BSkyB broadcast center (Fig. 32) located in west London houses the world first naturally ventilated television studios [76]. Thirteen giant ventilation chimneys, nine line the building's eastern elevation and another four appear on the west façade. Concrete boxes within boxes construction provides solution to eliminate external noise as well as naturally ventilate the studios to remove excessive heat generated by studio lights. Fresh air is supplied through acoustically lined labyrinth built in between the underside of the studio's concrete floor and the floor of the surrounding box from street level (see Fig. 33). This construction form allows big air paths to minimize resistance to air movement as well as eliminate all influx of noise.

In order to prevent a common stack ventilation problem – air cooling in the flue and dropping back into a room – the flues are lined and insulated on the inside. In an intermediate mode the ventilation system will run on extract only to pull the air up the chimney and warm it. When the right flue surface temperature has reached, the air's natural buoyancy will take over, the system then switch to natural ventilation mode automatically.

Natural Ventilation in Built Environment. Figure 32
BSkyB broadcast center in west London [76]



Natural Ventilation in Built Environment. Figure 33 Natural ventilation flow within the BSkyB television studios (*Source*: Arup Associates)

At the south end of the building, a glazed atrium houses a series of meeting rooms, a café, and breakout spaces, which allows access between levels. The office areas (8 m in depth) on the west elevation are ventilated using single-side natural ventilation. The offices (15 m deep) on the eastern side utilize three atrium-line chimneys in the center of the building to help draw air across the floor plates. Natural light through these atriums are additional benefit of the design.

Case Study 4: Commerzbank – Frankurt, Germany

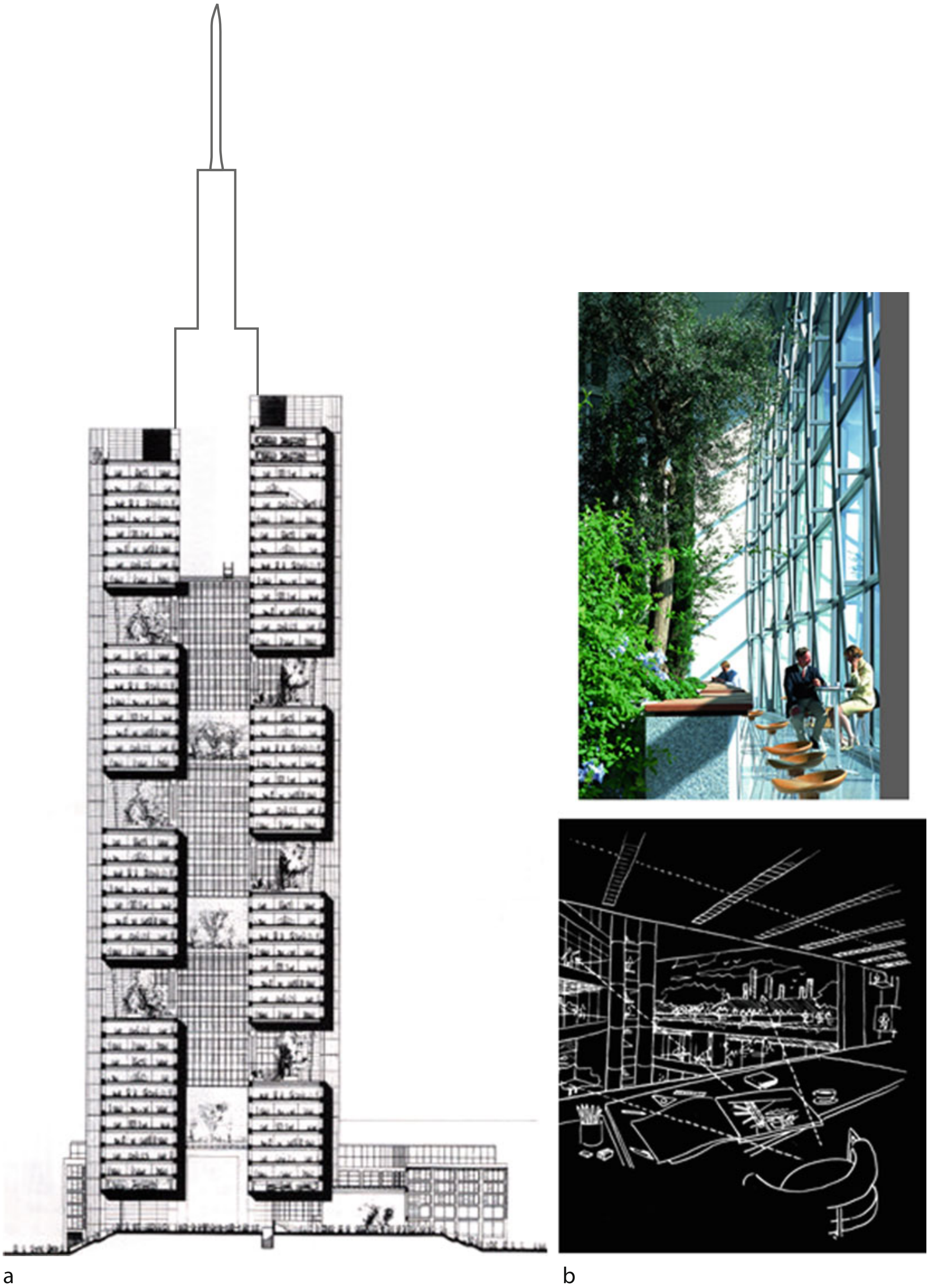
Norman Foster's Commerzbank in Frankurt, Germany (see Fig. 34), demonstrates sustainable urban architecture featured by natural ventilation, vast amount of daylight, and pleasant exterior views within deep building can be achieved at the scale of the skyscraper.

Triangular-shaped plan provide the rigid structural support with high-rise building functional cores located at each corner of this triangle. The center atrium of the buildings provides light both vertically, from the glass roof at the atrium's top, horizontally from the winter garden facades to the office areas. Winter gardens rotate around the façade of the building, allow for ventilation through the atrium being divided into sections. Natural light are brought directly into the center of the buildings, offices facing the center are provided light and outdoor views through these green, natural spaces. The operable layered façade allows natural ventilation through office spaces, while winter gardens provide ventilation for the entire building.

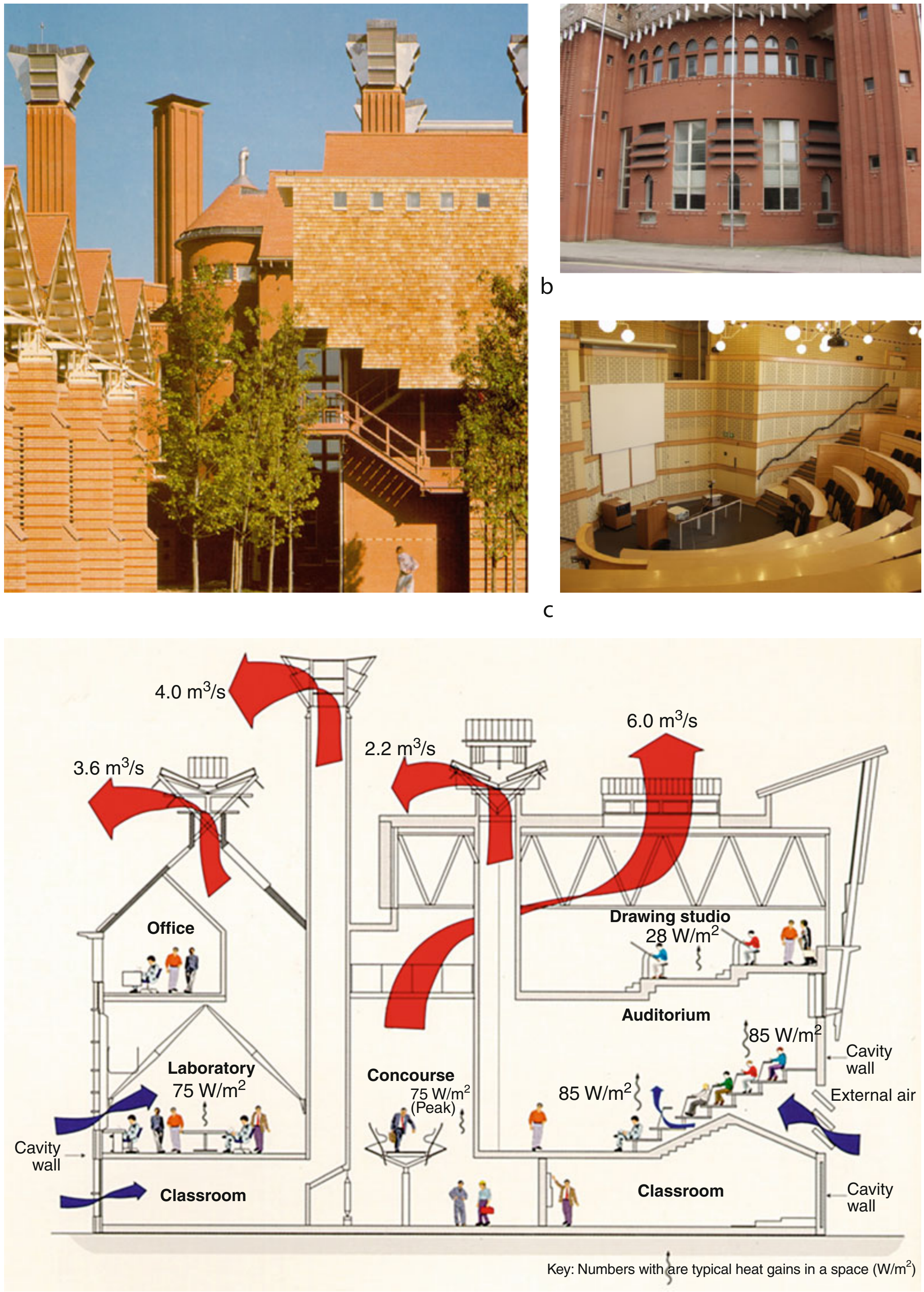
Case Study 5: Queen's Building, De Montfort University, UK

The Queen's Building (Fig. 35) designed by Short Ford Associates and built in 1993 featured with large venting chimneys, heavy thermal mass, shallow floor plan, operable windows, and generous ceiling heights to facilitate natural ventilation and daylighting. This traditional brick building has wide insulation-filled cavity walls and concrete slabs in the ceilings, buffering the indoor from outdoor temperature peaks. Glazed ventilators also help to provide as much natural lighting as possible. In the auditoria fresh air enters through louvers in the north façade by means of plenums below the raked wooden floor and wall inlets which are controlled by the BEMS.

Since being the Green Building winner of the Year 1995, Queen's building has served a great demonstration value for environmental design. It aims to a "Living Lab" to showcase innovative technologies and demonstrate ways of achieving significant carbon reductions in modern buildings through the refurbishment.



Natural Ventilation in Built Environment. Figure 34
Commerzbank, Frankurt, Germany (**a**) Building section [77] (**b**) Winter garden and interior view design [78]



Natural Ventilation in Built Environment. Figure 35
The Queen's building, De Montfort University, Leicester, UK (**a**) Exterior view and stack outlets; (**b**) Exterior view and air inlets; (**c**) Interior view of auditorium; (**d**) The Queen's building – natural ventilation strategy

Future Directions

Sustainable design requires a long-term durable approach and passive environmental control offers this. Holistic design and construction is necessary to achieve the sustainable built environment [79, 80], provide the optimum cost-benefit value for all stakeholders in the built environment industry. Natural ventilation should be explored as a possibility for all projects, but various factors can limit its use although, throughout history, vernacular architecture demonstrates it can work effectively in many climates but only if there is a unity of thought between architects and the engineers. However hybrid systems are common in Europe emphasized by the demand for low carbon buildings. Ultimately buildings are for people and systems must provide conditions for enhancing well-being at a time when climates worldwide are showing more variability and change.

Acknowledgments

The authors would like to thank Lee Hargreaves (WSP, UK Ltd.) for his help with researching and organizing some case studies; Mike Beaven of Arup Associates for some case studies; Matt Kitson (Hilson Moran) for providing Gherkin images; Professor Vivian Loftness (Carnegie Mellon University, USA) for providing architectural images and Fig. 21; Beifan Yang and Bin Zhang (Tianjin Weland Landscape Architecture Design Co, Ltd. China) for the architectural drawings; Jin Zhang (JINT Design Consultants Ltd.) for architectural sketch; and Dr Malcolm Cook (Loughborough University) for providing the images of Queens Building.

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Passive House (Passivhaus)

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Article Outline

Glossary

Airtight construction A method of construction for building envelopes that is aimed at the lowest possible result close to zero infiltration when tested for air leakage.

Balanced mechanical ventilation with heat recovery Highly energy efficient mechanical equipment for airtight homes to provide equal amounts of fresh air at all times to the inhabitants as well as to exhaust the same amount of air to remove moisture, stale air, and indoor pollutants while recovering the energy at the highest possible level, which is useful to maintain thermal comfort in the building.

Passive house building A building achieving close to thermal stasis by optimizing heat loss and gain through the building shell (primarily by limiting transmission losses through climate-specific insulation levels of its components and appropriate window specifications) so that thermal comfort in winter and summer can be maintained mostly without energy input and during the peak temperature periods with only very small amounts of energy input of roughly 1 W/sqft.

Superinsulation Adequate, climate-specific amount of insulation to balance heat gains and losses in a cost-effective manner.

Thermal Bridge free A building component, for example, a stud in a wall, is considered to be thermal bridge free when it has a lower conductivity than 0.006 BTU/(ft°F).

Definition of Subject

Performance based energy metrics and Passive Design Standards, history, development, methods and tools, current state of implementation, and future outlook.

Introduction

The Passive House Building Energy Standard is the most ambitious energy standard in the world. Buildings account for 40–50% of the total US carbon emissions – depending on how the sector is defined – stemming from buildings. The Passive House design and construction approach proposes to slash space conditioning energy consumption of buildings by up to an amazing 90–95% and overall energy use of space conditioning and household electricity by 70–80%, depending on which reference baseline home or energy code is used for comparison. Thousands of homes as well as educational and commercial buildings have been built or remodeled to meet the Passive House standard in Europe. Widespread application of Passive House design principles and construction methods in the USA – to both new construction and retrofit scenarios – would dramatically reduce the country's energy use and reduce carbon and other harmful admissions. And, structures built to the Passive House Building Energy Standard have a high quality, long lasting envelope, and in practice provide superior comfort and indoor air quality.

The Passive House Building Energy Standard actually evolved from the superinsulated buildings of the 1970s, many of which were built and pioneered in North America. The Small Homes Council of the University of Illinois (now known as the Building Research Council), developed the Low-Cal house in the late 1970s, and Wayne Schick, a member of the architectural faculty then, is credited with coining the term "superinsulation." A second group of early designs incorporated passive solar heating strategies instead of superinsulation primarily.

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The Canadian National Research Council and Minnesota's Housing Finance Agency were instrumental in supporting the construction of very low-energy prototypes and in launching of low energy programs like R2000. The history and list of early adopters and realized projects in Canada as well as in the USA is extensive as also the accompanying research, and would warrant a book in itself. By the end of 1986, an estimated 10,000 very low-energy homes had been built in North America. Many of these early prototypes are still around today and provide excellent long-term experience with this construction type. They are, to this day, comfortable, energy-efficient homes with very good indoor air quality (IAQ) and long-lasting, high-quality envelopes.

However, it was in Europe – in the early 1990s – that pioneering concepts like superinsulation and passive solar approaches were further refined into a comprehensive approach called Passivhaus in Germany. It was a quantum leap triggered by the passage of an ambitious, rigorous energy standard in 1988 for new buildings in Sweden. Other European countries later followed suit in tightening their energy codes significantly. In response to the new Swedish standard, Swedish professor Bo Adamson and German physicist Wolfgang Feist envisioned a building that could meet and even exceed this standard – the Passive House. Construction on the first prototype, a four-unit row house structure, started in 1989 in Darmstadt, Germany. It was completed in 1991. Then as now, the primary components of a Passive House were thick insulation, few or no thermal bridges, an airtight envelope, excellent insulated glazing, and balanced heat recovery ventilation.

The Early Developments in North America Inspired Europe

The term "Passive House" seems to have originated in Canada and the USA. In the 1970s and 1980s, the term "Passive Housing" was a well-known scientific term describing a combined approach of superinsulation and measured passive solar strategies minimizing space conditioning to extremely low loads. The term was translated into *Passivhaus* in German and was kept as the design principles were optimized by Feist and Adamson. They understood the term to be appropriate to describe a holistic design strategy. Tailored to the moderately cold, heating-dominated Central European climate, it aimed at requiring so little energy to heat to comfortable conditions that a conventional heating system could be eliminated. Instead, a single 1,000-W post-heating element in a balanced supply ventilation stream provided all the heating requirements for a home of approximately1,000 ft or 100 m. The annual total heating demand could be minimized by making careful use of existing internal heat sources – people, lights, and appliances; and optimized (not maximized) solar energy admitted by the windows. A fresh-air heating supply would be pre-warmed by highly efficient heat recovery from the exhaust air, and also in the earlier Passive House projects in Europe by an earth tube, which is a passive geothermal heating-and-cooling system (also intended to prevent the heat exchange core of the ventilation system from freezing).

Early prototypes were designed so that the maximum heat load in the German winter was to be less than 10 Watt per square meter (W/m^2), or 0.9 watts per square foot (W/ft^2), of floor area. Under these circumstances, the heat load could be comfortably supplied using fresh-air ventilation – eliminating the need for a separate means of heat distribution. On the active solar and renewable side, cost-optimized solar thermal systems for hot water production were specified but there was no necessity or emphasis on any active-solar contribution such as photovoltaic. It was recognized early on that the additional investment cost for Passive House measures to conserve energy were far less and more cost-effective than active photovoltaic systems to reduce energy consumption. Passive House as a conservation baseline has since been recognized in the European Union to be the most cost-effective way to achieve near zero or zero energy buildings. Supported by research grants from the German state of Hessen, Dr. Feist created detailed computerized simulations modeling the energy behaviors of wall and window assemblies and other construction elements. Then he systematically varied these elements to arrive at the best possible construction packages, based on energy efficiency, installation expense, and sustainability.

In 1995, Amory Lovins – himself an American energy pioneer and founder of the Rocky Mountain Institute – visited the optimized Passive House prototype at Darmstadt and was deeply impressed. Lovins had implemented Passive House principles in his own home, and saw in Feist's work more than a concept. He encouraged Feist to use the project as a basis for a practical way to meet energy needs for a broad range of implementation. All that was needed was to redesign some details to reduce construction costs.

In 1996, Dr. Feist founded the Passivhaus Institut (PHI) in Darmstadt. The PHI has flourished under his leadership, designing, testing, calculating, certifying, and analyzing data on buildings constructed to the Passive House standard, and their components. The Passive House Planning Package (PHPP) is the Institut's energy-modeling program. The methodology used in this program is profoundly thorough and balanced for interdependencies, and it has been used to design thousands of projects of all building types across Europe. The measured energy performance of the homes has been shown to closely match the modeled performance predicted. The PHPP modeling tool is the most accurate and simple-to-use design software available today to predict the energy consumption of extremely low load homes. Its granularity has been calibrated to see the smallest design effects on the energy performance of a building. Some of those effects are precise calculation of transmission losses through all components of the thermal envelope, solar gains, shading, thermal bridging effects, the influence of thermal mass, ventilation losses, systems efficiencies, and ventilation system design for minimized fresh air conditioning.

The Passive House Building Energy Standard defines the lowest energy metric and standard worldwide. It requires that a building use no more than 15 kilowatt-hours per square meter (kWh/m^2) per year in heating and cooling energy, which is equivalent to 1.35 kWh/ft^2 or 4.75 thousand British thermal units per square foot (kBtu/ft^2) annually. It further requires that the building's total primary energy consumption – that is, source energy used for space conditioning, hot water, and electricity – not exceed 120 kWh/m^2 (10.8 kWh/ft^2 or 38 kBtu/ft^2) per year.

The energy metric is in reference to the interior treated floor area minus circulation spaces and discounted storage and mechanical spaces. Passive Houses also tend to have thicker exterior envelopes than typical construction, and the energy calculation is more accurate if they are excluded. It is important to note that most modeling tools in the USA use the exterior dimensions of a building to determine the per-square-foot energy metric of a building. This has led to some confusion in comparing the Passive House energy metrics to commonly used energy intensity units in the USA. Typically, if put in relation to the exterior building dimensions – as is customary in US energy modeling, the Passive House metric is approximately 20–30% lower than the certification requirements mentioned above, depending on size and design of the building. Using exterior building dimensions, the Passive House metric would result in roughly 3.4 kBtu/ft^2 annually for the total space heating and cooling demand and in roughly 28 kBtu/ft^2 annually for the source energy requirement.

Structures built to the Passive House Building Energy Standard – and the techniques and products developed for them – were further popularized in Europe through the European Union-sponsored Cost Efficient Passive Houses as European Standards (CEPHEUS) project, which validated that the Passive House concept worked in five European countries over the winter of 2000–2001. Thousands of Passive Houses have been built across Europe, as interest in the benefits that they provide has skyrocketed. Many provinces and cities there are now mandating that all new construction built with public monies be built to the Passive House Building Energy Standard. The European Union has proposed to adopt the Passive House Building Energy Standard Europe-wide to meet their action plan, which calls for near zero energy buildings by 2020 for all new construction.

Recent Developments in the USA and Canada

In the spring of 2002, German-born architect Katrin Klingenberg traveled from the USA, where she has lived since 1994, to Germany to tour Passive Houses with Manfred Brausem, a leading architect and Passive House pioneer there. An ardent advocate of sustainable architecture, Klingenberg was powerfully affected by what she saw. She returned to the USA and began designing her own Passive House, the Smith House, which broke ground that October in Urbana, Illinois.

In 2003, Klingenberg attended the Seventh International Passive House Conference, in Hamburg, where she met Dr. Feist. She returned to finish the Smith House, which became the first Passive House in North America that used the Passive House Planning Package software as a design tool. Monitoring devices installed at the Smith House after its completion confirmed the predictions:

- The house uses only 11 kWh/m^2 (1 kWh/ft^2 or 3.5 kBtu/ft^2) per year in heating energy (in reference to the Passive House interior treated floor area).
- The highest monthly energy use ever for space and water heating, appliances, and lighting – in short, for all purposes – was 599 kWh.
- With an average electrical base load of 265 kWh, the highest monthly energy use for space heating has been 334 kWh.

The construction of the Smith House was successful in more than just one way. It confirmed the applicability and accuracy of the European-developed design tool for this North American location, as well as cost-effectiveness and relative ease of transfer to local construction techniques.

In 2005, Stephan Tanner, a Swiss-born architect started working on the first American school Passive House building, the BioHaus in Bemidji, Minnesota – located in an even more challenging climate. Designed as a learning facility for the German-language Concordia Village, the BioHaus succeeded in meeting the Passive House Building Energy Standard and was certified in 2006. In October 2006, Klingenberg and Tanner teamed up to organize the first North American Passive House conference at the BioHaus in Minnesota. Interest was piqued; new projects were started.

Climate-Changing Opportunity

In April 2007, Klingenberg and Passive House builder Mike Kernagis cofounded the Passive House Institute United States (PHIUS) to disseminate information about, and promote the construction of, Passive Houses and Buildings in North America. They steadily promoted the Passive House standard at symposia, workshops, and conferences from coast to coast. Passive House projects have been built in the full range of North American climates since, from Fairbanks, Alaska to Lafayette Louisiana. Although most Passive House construction to date consists of new buildings, a few retrofit projects have been started as well. By mid-2011, there were a total of 22 certified Passive House projects in the USA, with two in Canada registered. More than 100 others from the USA and Canada have applied for pre-certification and are in progress. More than 500 professionals have taken the certification training to become a Certified Passive House Consultant; the number who have taken and passed the final rigorous exam has surpassed 200.

Passive House design and construction methods and the overall approach to homebuilding best meet today's energy and environmental needs worldwide. The Passive House concept is a timely and powerful solution that is now quickly gaining traction in the USA and Canada. Many Passive House projects in this country are so new that empirical data on their energy performance are limited, but extensive data on the energy performance of Passive Houses in Europe are available, through the CEPHEUS project at www.cepheus.de/eng/index.html. According to Guenter Lang, the former executive director of the IGPassivhaus Austria, a member-based interest group, Austria would reach a projected 25% market penetration of Passive House Buildings for new construction by the end of 2010. In the USA, various Building America teams are involved in monitoring the early Passive House projects and many have completed their first year of data collection. Soon there will be publications available on measured Passive House performances in the USA and Canada.

Early indications from that data suggest strongly that adoption of the Passive House Building Energy Standard will continue to accelerate in North America. The PHIUS, the existing North American Passive House community – active consultants organized as the National Passive House Alliance a membership organization – and future Passive House adopters together face a terrific opportunity and an enormous challenge. For the Passive House Building Energy Standard to become the prevalent energy performance standard, it is critical that:

- Training and continuing education opportunities grow to meet the need.

- Experiences in North America's diverse climate regions are measured and shared with the building community. That experience must drive continual refinement of Passive House design principles, construction techniques, component design, and manufacture to meet the special requirements of each climate zone.
- To maintain integrity in the marketplace, rigorous project and professional certification programs must be maintained and subscribed to.

Principles of Passive House Design

The Passive House concept is a comprehensive approach to cost-effective, high quality, healthy, and sustainable construction. It seeks to achieve two goals: minimizing energy losses and maximizing passive energy gains. A Passive House requires *up to* 95% less energy for space heating and cooling than a conventionally constructed house. To attain such outstanding energy savings, Passive House consultants and builders work together to systematically implement the following seven principles:

- Superinsulation (depending on climate).
- Eliminating thermal bridges.
- Airtight construction.
- Heat or energy recovery ventilation (depending on climate).
- High-performance windows and doors (depending on climate).
- Optimization of passive-solar and internal heat gains (depending on climate).
- Calculating the energy balance.

Superinsulation

The insulation applied to a house works in much the same way as the insulation in a thermos bottle. In both cases, the insulating outer shell or envelope blocks or slows heat transmission and maintains the contents at a relatively constant temperature. Warm contents stay warm, cool contents stay cool, even when the temperature on the outside hits one extreme or another. In a building constructed to the Passive House standard, the entire envelope of the building – walls, roof, and floor or basement – is well insulated.

How well insulated? That depends, of course, on the climate. To achieve the Passive House standard, a home in Sonoma, California, required only 6 in. of blown-in cellulose insulation to meet the standard, while a home in the far colder climate of Urbana, Illinois, needed 16 in. – almost three times as much. Often, the first feature of a Passive House to catch a visitor's attention is the unusual thickness of the walls. This thickness is needed to accommodate the required level of insulation.

The Comfort Principle Thermal comfort in summer and winter is the focus for determining the required thickness of the insulation based on climate. Human thermal comfort in a building depends on many factors, but most commonly and directly perceived according to air temperature in the space and air movement. If the mean radiant surface temperature of a building's exterior wall components is way below the surface temperature of the interior walls, then there is convection induced. If there are convective currents from warm to cold then the consequence is stratification: different temperatures near the floor of a room compared to the ceiling, or significant differences in first floor temperatures and second floor temperatures. In addition, if exterior walls are cold, then the human body starts to lose heat to the colder exterior surfaces by radiation, which leads to discomfort and feeling cold in winter. In summer, the hot exterior surfaces radiate to the interior.

There is an easy solution to this problem: maintaining the exterior surface temperature uniformly at a level so that convection is nearly eliminated. By determining the set points for the interior room temperature for summer and winter comfort, and looking at the summer and winter design temperatures in any given climate, the R-value can be calculated so that the exterior wall temperature even during the coldest design day in winter or warmest in summer will remain within the acceptable range. In a Passive House, the difference in temperature of exterior and internal wall surfaces should not exceed 4°F to always maintain human thermal comfort.

Insulation Materials Choices Even with this insulation requirement, Passive House designers have a wide range of choices for the materials used to create superinsulated building envelopes for various climates. Wall assemblies can be built using conventional lumber or masonry construction, double-stud construction, structural insulated panels (SIPs), insulated concrete forms (ICFs), truss joist I-beams (TJIs), steel or concrete frame, or straw bale construction.

Similarly, designers can choose from a number of different types of insulation. These include cellulose, high-density blown-in fiberglass, polystyrene, spray foam, and again straw bale. Although spray foams have a high R-value and are easy to apply, many builders prefer not to use them because they are petroleum-based products, have high embodied energy, and because the currently market dominant expansion agents can contribute significantly to global warming. Manufacturers are seeking to develop spray foams that do not have these disadvantages. Vacuum insulated panels (VIPs) are a relatively new, and still pricey, option with an exceptionally high R-value per inch. Using VIPs allows designers and builders to greatly decrease the thickness of the walls in homes where that is a consideration. Still higher-tech insulations are in development such as aero gels.

No matter which type of insulation gets chosen, Passive House builders need to make sure that the product is installed correctly. It is important to assure and measure the proper density on site before insulation is blown in if loose fill insulation such as cellulose or high density fiberglass is being used to prevent any settling. In any case, with or without having measured the installed density during the insulation process, the application and performance of insulation can be directly measured using thermographic imaging. All objects emit infrared (IR) radiation, and the amount of radiation emitted increases with the temperature of the object. Variations in IR radiation, and therefore in temperature, can be observed using a thermographic, or IR, camera – a useful tool for testing buildings during the quality assurance process. Since these cameras can readily detect heat loss, they can usually identify areas where insulation is insufficient, incomplete, damaged, or settled. Technicians who read thermal images of properly constructed Passive Houses have jokingly called them boring, as they often reveal little substantive heat loss.

Eliminating Thermal Bridges

Heat loss follows the path of least resistance: Heat will pass very quickly through an element that has a higher thermal conductivity than the surrounding material, forming what is known as a thermal bridge. Thermal bridges can significantly increase heat losses, which can create areas in or on the walls that are cooler than their surroundings. In the worst-case scenario, this can cause moisture problems: when warm, moist air condenses on a cooler surface.

Thermal bridges occur at edges, corners, connections, and penetrations. A bridge can be as simple as a single lintel that has a higher thermal conductivity than the surrounding wall or several steel wall ties that pass through an envelope. A cantilevering balcony slab that is not insulated from, and thus thermally isolated from, an interior concrete floor can be a potent thermal bridge. An effective thermal isolation is called a thermal break. Without a thermal break, the balcony will act as a very large cooling fin – in the wintertime!

In a Passive House, there are few or no thermal bridges. When the thermal bridge coefficient, which is an indicator of the extra heat loss caused by a thermal bridge, is less than 0.01 watts per meter per Kelvin (W/mK) or 0.006 British Thermal Units per hour foot and degree Fahrenheit (BTU/h ft °F) , the detail or wall assembly is said to be thermal bridge free. Additional heat loss through this detail is negligible, and interior temperatures are sufficiently stabilized to eliminate moisture problems and to meet the comfort criteria. It is critical for the Passive House designer and builder to plan for reducing or eliminating thermal breaks by limiting penetrations, and by using heat transfer-resistant, thermally broken materials. Here also, thermographic imaging during the quality control visits can be used to determine how effective the efforts to eliminate thermal bridges have been.

Airtight Construction

Airtight construction helps the performance of a building by reducing or eliminating drafts – whether hot or cold – thereby reducing the need for space conditioning to maintain comfort. Airtightness also helps to prevent warm, moist air from penetrating the structure, condensing inside the wall, and causing structural damage.

Airtight construction is achieved by wrapping an intact, continuous layer of airtight materials around the entire building envelope. Special care must be taken to ensure continuity of this layer around windows, doors, penetrations, and all joints between the roof, walls, and floors. Insulation materials are generally not airtight and that includes spray foams. The materials used to create an intact airtight layer include various membranes, tapes, plasters, glues, shields, and gaskets. These materials are durable, adherent, easy to apply, and environmentally sound, which in turn makes it easier for a builder to meet the stringent airtightness requirement of the Passive House standard.

Airtightness of a House: A Measurable Dimension of the Quality of Construction Testing airtightness requires the use of a blower door, which is essentially a large fan used in conjunction with sensitive measuring instruments. The blower door can be used to either depressurize or pressurize a house to a designated pressure. With the fan set to maintain this designated pressure, a technician can assess how much air is infiltrating the building through all its gaps and cracks. Specific leaks can be detected during the test either by hand, by employing tracer smoke, or by looking at thermographic images if there is a temperature difference between inside and outside. It is best to conduct the blower door test at a point in construction when the airtight layer can still be easily accessed, and any leaks can be readily addressed.

Passive Houses are extremely tight. At a standard test pressure of 50 Pa, a building that meets the Passive House standard must allow no more that 0.6 ACH *(Air Changes per Hour)* in order to achieve certification. Projects that have successfully met the Passive House standard have been built from timber, masonry, prefabricated elements, and steel or concrete frame buildings with superinsulated curtain walls.

The tightness standard of 0.6 ACH50 is not an arbitrary measure. As walls get superinsulated and airtightened, they become more prone to moisture damage. The typical vapor profile and drying potential changes, sometimes significantly. Consequently, 0.6ACH50 has been determined to be the safe limit for superinsulated walls even in very cold climates to avoid moisture damage through infiltration and diffusion.

Airtightness does not mean that one cannot open the windows. Passive House building have fully operable windows, and most are designed to take full advantage of natural ventilation to help maintain comfortable temperatures in the spring, fall, and even the summer, depending on the local climate.

Heat or Energy Recovery Ventilation

Perhaps the most common misperception regarding Passive Houses concerns air flow. "A house needs to breathe," builders might say disapprovingly, when first presented with the idea of building very tight homes. Buildings that meet the Passive House standard do breathe – exceptionally well. However, rather than breathing unknown volumes of air through uncontrolled leaks, Passive Houses breathe controlled volumes of air by mechanical ventilation. Mechanical ventilation continuously circulates measured amounts of fresh air through the house and exhausts known quantities of stale air from the house. This makes for excellent IAQ. The amount of air exchanged is strictly based on the exchange necessary to assure that all pollutants get sufficiently removed. Only the air needed for excellent IAQ is exchanged. The health and comfort of the occupants come first for the Passive House designer, and excellent IAQ is indispensable for occupant health.

A Passive House building is ventilated using a balanced mechanical ventilation system. Needless to say, this ventilation system must be extremely energy efficient. To that end, Passive House designers specify energy recovery ventilators (ERVs) or heat recovery ventilators (HRVs) in cold, dry, and marine climates. These machines incorporate an air-to-air energy recovery system, which conserves most of the energy in the exhaust air and transfers it to the incoming fresh air. This significantly reduces the energy needed to heat that incoming air.

State-of-the-art ventilation systems have measured and verified heat recovery rates of 7,592%. The energy consumed by the motor of the ventilator is also considered. To avoid a total net loss of input energy versus heat recovery effectiveness, the efficiency of the motor needs to be extremely high. The energy efficiency limit for Passive House ventilation system motors should meet 0.45 watt hours per cubic meter (Wh/m^3) of air or 0.76 watts per cubic foot and minute (W/cfm) of air.

The ventilation system generally exhausts air from the rooms that produce moisture and unwanted odors, such as the kitchen and bathrooms. The flow rate is set to a low level. For a typical single family home, the base airflow rate is approximately 90–120 cfm total. Timed overrides are typically installed in the exhaust rooms to allow the user a short period of time to increase the ventilation flow rate if moisture or odor levels are elevated. The exhaust air gets drawn through the ventilator on its way out of the building. There it passes through a heat exchanger that transfers the reusable heat energy to the incoming fresh air. It is important to note that the exhaust air is not mixed with the incoming air; only its heat is transferred. Acceptable contamination of the two air steams is limited to 3% max. While return air is circulated back to the furnace in a forced air system, no air is recirculated with a mechanical ventilation system. All supply air is fresh air.

When operating, the ventilator constantly provides a steady supply of fresh air. At the same time, it removes excess moisture, CO_2, other pollutants like VOCs from furniture, unwanted odors and even radon. The incoming air is filtered and balanced. Filtration is important for indoor hygiene as well as for a long-lasting ventilation system. Passive Houses have a requirement of a minimum filter quality of F7 (Europe) or MERV 11. The air is distributed at the low flow rate through small, unobtrusive, but highly effective, diffusers. The system is generally very quiet and draft-free. Dust circulation is minimized. The PHPP recommends an ACH of 0.3–0.4 times the volume of the building, and a guideline ACH of 30 cubic meters (m^3) per person.

The main difference between an HRV and an ERV is that the HRV conserves heat and cooling energy, while the ERV does both and transfers humidity as well. In summer, an ERV helps keep the humidity outside; in winter, it helps prevent indoor air from becoming too dry. For in-between seasons, when no conditioning is needed, a bypass can be installed for either system to avoid heating the incoming air. Alternatively, the ventilation system can be turned off altogether, and windows can be thrown open to bring in fresh air.

Either system's efficiency can be increased by pre-warming or pre-cooling the incoming air. This is done by passing the incoming air through earth tubes. Since the ground maintains a more consistent temperature throughout the year than the outdoors, passing the air through tubes buried in the earth either pre-heats or pre-cools the air, depending on the season. Pre-heating and pre-cooling can also be accomplished indirectly, by circulating water in an underground pipe and using it to heat or cool the air with a water-to-air heat exchanger integrated with the intake air stream between the ventilator and the envelope. This way, potential condensate in humid climates can drain in a controlled location rather than occurring in the earth tube.

High-Performance Windows and Doors

In modeling the energy balance of a building, the designers of Passive House buildings choose windows and doors based largely on their insulating value. At one time it was hard to find doors and windows that had the exceptional insulating properties required by the Passive House comfort and the few that existed were very expensive.

That is no longer the case. There have been extraordinary advances in window quality over the past 30 years, and thermal losses from windows have dropped dramatically even for North American products. Many brands of windows and doors are now being made tighter, reducing losses through infiltration and exfiltration. Doors have been provided with appropriate thermal breaks and double gaskets. Overall, high-performance windows and doors are proving to be cost-effective in Passive House applications.

One development that has significantly affected the heat conductivity of window glazing is the introduction of low-emissivity (low-e) coatings. These are microscopically thin, transparent layers of metal or metallic oxide deposited on the surface of the glass. The coated side of the glass faces into the gap between two panes of a glazed assembly. The gap is filled with low-conductivity argon or krypton gas rather than air, greatly reducing the window's radiant heat transfer. Different low-e coatings have been designed to allow for high, moderate, or low solar gain. This provides a range of options for houses in all climates, from heating dominated to cooling dominated. Today, builders can choose to install triple-pane low-e-coated, argon-filled windows with special low-conductivity spacers and insulated, thermally broken frames. These windows eliminate any perceptible cold radiation or convective cold air flow, even in periods of heavy frost. For the moderate cool climate (climate zone 4) and the central European climate a U-value of 0.85 (W/m^2K) or 0.15 BTU/h ft^2 °F is recommended for the entire installed assembly accounting for frame values, glass values, spacer and installation thermal bridge effects.

Optimization of Passive-Solar and Internal Heat Gain

Not only must designers of Passive House buildings minimize energy loss, they must also carefully manage a home's energy gains. The first step in designing a Passive House is to consider how the orientation of a building – and its various parts – will affect its energy losses and gains. There are many issues to be considered. Where should the glazing be to allow for maximum sunlight when sunlight is wanted, and minimal heat gain when heat gain is unwanted? The more direct natural lighting there is, the less energy will be needed to provide light. Designers can enhance residents' enjoyment of available sunlight by orienting bedrooms and living rooms to the south, and putting utility rooms, closets, and circulating spaces, where sunlight is not needed, to the north.

However, it is not always possible to site a house in this ideal way. There may be buildings, trees, or landforms that cast shadows during short winter days, blocking out much of the low sunlight. Or the designer may need to accommodate the homeowner's demand for a certain view – a view that would not be available in an ideal orientation.

Windows are designed, oriented, and installed to take advantage of the outstanding passive solar energy that can be gained through them. But the goal is not simply to allow for as much solar gain as possible. Some early superinsulated buildings suffered from overheating because not enough consideration was given to the amount of solar gain that the house would experience. A good design should balance solar gain within the home's overall conditioning needs – and within the glazing budget. Even very efficient windows can lose more heat over a year than they gain, depending on their location, and large windows are expensive. In the northern hemisphere, in climates with cold winters, windows on the north allow for no direct solar heat gain, while those on the south allow for a great deal of it. In summertime, and in primarily cooling climates, it is very important to prevent excess solar heat gain. This can be done by shading the windows. Roof eaves of the proper length can effectively shade south-facing windows when the sun is higher in the summer, and still allow for maximum solar heat gain in the winter, when the sun is lower and the days are colder. Deciduous trees or vines on a trellis can also block out sunlight in the summer and admit it in the winter. In climates that have a significant cooling load, the designer should consider limiting unshaded east- and west-facing windows, and specifying only windows that have low-solar-gain, low-e coatings. During the morning and late afternoon, low-angle sunlight can generate a great deal of heat in such windows. A guiding value for Passive House solar gain optimization in colder climates is the recommendation of a solar heat gain coefficient of approximately 50% or slightly higher, in cooling climates it should be below 30%.

Another, perhaps less obvious, source of heat gain is internal. Given the exceptionally low levels of heat loss in a Passive House, heat from internal sources can make quite a difference. Household appliances, electronic equipment, artificial lighting, candles, people – all can have a significant effect on the heat gain in a Passive House. While designers may not be choosing how many or which appliances will be installed in a house, designers often select lighting sources, and must take into account these heat gains when calculating the overall internal energy gains.

Energy Balancing – Modeling with PHPP (Passive House Planning Package)

There are many elements of Passive House design that need to be integrated with one another. They include wall thickness, R- or U-values, thermal bridges, airtightness, ventilation sizing, windows, solar orientation, climate, and energy gains, and losses. Modeling software for Passive Houses needs to facilitate accurate energy use prediction helping a designer to integrate each of these components into the design so that the final design will meet Passive House requirements and the projected performance. One starts with considering the whole building as one zone for the energy calculation. The designer considers all of the house's basic characteristics, including orientation, size, window location, insulation levels, and so on. One then computes the energy balance of the design and calculates the equivalent "miles per gallon" energy consumption for the house. If needed, the designer can change a house's components – window location or size for example – and model the impact of those changes on the overall energy balance.

Out of all energy balancing models out there, the PHPP, Passive House Planning Package, developed by the Passivhaus Institut in Germany, is a very responsive what-if tool, allowing designers to readily shift the variables of design to reach these goals. It also effectively models such things as solar water heating for combined space heating and domestic hot water, natural ventilation such as night cooling, and the efficiency of heat/energy recovery ventilation. The PHPP incorporates an impressive depth and level of detail when considering the variables that create a building's unique energy balance. Other modeling tools on the market are starting to incorporate similar strategies increasing their calculation granularity to calculate the energy balance of extremely low energy buildings accurately and could be used to calculate Passive Houses as well.

A Word on Cooling and Dehumidification The Passive House Building Energy Standard was developed primarily in Central Europe, which has a relatively mild, primarily heating-oriented climate. Implementation of designs that meet the Passive House standard is more challenging in climates of more extreme cold, heat, or humidity. Already, many Passive Houses have been built in extremely cold climates, a few Passive Houses have been completed in hotter climates and more are being submitted for certification review.

In cooling load (as in heating load) situations, the space conditioning load must be minimized. This takes careful planning. As explained earlier, the high levels of insulation in a Passive House help to keep indoor temperatures cool. In addition to the standard measures for preventing excess solar gain, convective venting behind siding and roofing and night cooling will often help to maintain indoor comfort. In humid climates, an additional cooling load may stem from the need to remove latent moisture from the air. A very small and efficient air-to-air heat pump – also known as a mini-split – can remove this moisture and provide adequate cooling. In extremely humid climates, such as in Louisiana, additional dehumidification might be necessary.

Economic Sustainability Passive House design focuses on balancing energy gains and losses in order to attain a level of energy efficiency that is far beyond the norm. But the norm is changing, and many people now recognize that energy efficiency is profoundly important, both economically and environmentally. It has been called a low-hanging fruit, an innovation that can, and should, be readily attained.

This focus on energy efficiency makes Passive Houses more expensive to build. Construction costs generally run 10–15% higher for single family homes than the costs for conventional houses. The additional upfront costs for more insulation, better windows and doors, and more labor for higher quality installations are partially offset by the lower cost of the heating and cooling systems. Because Passive Houses have such small heating and cooling requirements, conventional heating and cooling systems can be replaced with miniaturized components and efficient mechanical ventilation. This is one example of how the integrated planning required to build a Passive House helps builders to "tunnel through the cost barrier," in the words of Amory Lovins. The additional construction cost is readily recovered in savings on the homeowner's energy bill. These savings will continue throughout the life of the house. And – perhaps most important in the long run – the Passive House will generate a carbon footprint that is a fraction of the size of that of a conventional house. On-site renewable energy resources can be added to create a true zero-energy, or even plus-energy, house – one that produces more power than it consumes.

In the past, most homes were built with scant attention paid to their long-term energy consumption. This approach needs to change. It is important to use our limited natural resources wisely and to build our homes with quality and durability in mind. The costs of energy consumption are high, and they are going higher. The savings to be realized over the life of a Passive House are remarkable, both economically and environmentally.

Future Directions of Passive House in the USA, Canada, and Internationally

The Passive House Institute US was the first outpost in North America that made it its mission as a nonprofit organization in 2007 to increase the number of ultra energy efficient buildings in the USA by promoting the adoption rate of the Passive House Building Energy Standard. The organization has worked diligently with limited capacities to provide services such as Certification, Design, Training, Education, and Research nationwide. The National Passive House Alliance, a nationwide membership organization focuses on educating its members and the general public on the topic, improving the recognition of Passive House construction and principles in various legislative programs, and providing continuing education opportunities to its members. Since 2008, the number of Certified Passive House Consultants in the USA and Canada has been exponentially growing. The demand is expected to increase significantly over the next years. Passive House buildings in the certification process in the USA are now representing commercial and residential buildings in almost all NA climate zones. This number also continues to grow rapidly. Now, also other organizations and the government have become interested, such as the USGBC as well as federal and state legislators, to include Passive House as a Low/Net Zero Energy alternative into their programs.

The success and fast uptake over the past 4 years of a performance-based energy metric clearly defining the level of conservation that should be reached was surprising. It has made it clear that there is the need in the market to increase capacity to train professionals as well as students in the field of Passive House design and construction. This not only helps Passive House to meet environmental needs but it is also a way to reclaim many jobs in the construction industry that were lost in the housing melt down.

While the initial success in North America is hopeful it is also a reason to be cautious. There is an increased need for the output of quality publications and design guidelines documenting especially the experiences of Passive House designs in North American climates to date and to increase monitoring programs of larger developments in various climates that will serve as proof of concept. In conclusion, it can be said that the Passivhaus standard, as it is known today in central Europe, was developed in a relatively easy and homogenous climate, a climate most closely resembling the climate in the North West of the USA. The recent Passive House iterations of the USA and Canadian projects have shown that still a lot of research and transfer is needed to assure an equally successful and widespread dissemination of the concept, especially in the very cold and humid, mixed humid, and hot humid climates of the USA where the energy savings potentials from conservation are extremely high. It is to be expected that there will be variations on the theme from the central Europe so successful core Passive House metric developed in Germany. Here, in North America, the movement is just beginning its way to Main Street.

Internationally, the implementation of the principles in different countries poses new challenges altogether. Existing building culture, exiting building components in the market, and cultural acceptance of the Passive Design standards will play a big role in how far the concept can continue to grow internationally also. Many initial groups have formed from New Zealand to China and Russia disseminating the knowledge similarly to what PHIUS has done in the USA over the past 6 years. The International Energy Agency, headquartered in Paris, France, has invested a lot into research on how to guide and make recommendations to governments with regard to the implementation of highly efficient building codes aiming at envisioning cost-effective zero energy buildings by 2030 as an international goal. The successful strategy will most likely be a coordinated guided code implementation approach coupled with a grass roots effort from organizations and individuals working from the bottom up.

For More Information

The Passive House Institute United States (PHIUS) is a nonprofit certifying, consulting, and research firm working to further the implementation of Passive House Building Energy Standards nationwide. For information about the institute, go to www.passivehouse.us.

Passive Solar Heating in Built Environment

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Article Outline

Glossary

Solar architecture The deliberate use of solar energy by means of the building architecture, thereby reducing purchased energy dependence while enhancing the quality of enclosed space.

Passive Not requiring actions to achieve a desired goal. In the case of passive solar energy use, solar energy is captured and distributed in a building without machinery by using the physics of conduction, free convection, and radiation.

Direct gain The direct gain of heat within a building by sunlight entering through glazed openings in the enclosure, which then traps and stores the heat.

Indirect gain Solar energy absorbed in some fashion on or in walls or roofs and converted to heat. This heat either remains entrapped in the building envelope to reduce building heat losses, or it is transferred into the building by conduction or convection. There may be a delay between the time when sunlight is absorbed and when heat penetrates into the enclosed volume.

Isolated gain Solar energy absorbed outside the insulated building envelope and then transported by free convection to the enclosed volume.

Solar air system Type of isolated gain system where heat from the collector transported to the point of use or storage by air (verses water in active thermal systems).

Hybrid solar system A passive system assisted by a small fan to increase system efficiency, possibly PV-powered. The energy ratio of heat output to electrical input can easily exceed 20:1.

Definition and Importance of Passive Solar Heating

Passive solar heating is the use of solar energy to heat a building without mechanical or electrical energy. The architecture and construction capture, store, and distribute the sun's energy. Every building with windows exposed to the sun is passively heated, but heat losses may exceed the solar gains. Accordingly, if the passive heat gain is to reduce heating costs, the system heat losses must be minimized. Ideally, the concept includes mass to store daytime solar heat for nights, increasing the usability of the gains. Finally, the heating system must shut off when solar heating achieves the desired room temperature. Two constraints on passive solar use are glare control and shading during non-heating months.

Maximizing usable passive solar gains is an important design aspect, but often designers focus only on minimizing heat losses. Taking the finance world as an analogy, no one will accumulate wealth through savings alone, income must be maximized and wisely invested. So, not only reducing heat loss is essential to low energy architecture, maximizing solar gains is important, as it has been over the history of building.

An often cited early example of solar design awareness is the "Megaron House" described by Socrates in the year 400 B.C. Numerous other examples can be found, i.e., the New England "salt box" of the seventeenth century or Swiss farm houses of the eighteenth century. In the twentieth century, the term "solar house" became popular and following the first oil

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Passive Solar Heating in Built Environment. Figure 1 A living room flooded with sunlight from large south-facing windows (photo source: robert.hastings@aeu.ch)

shock of 1973, the term "passive solar buildings" was coined. In all these examples, the basic principles are the same; maximize the south exposure of a building to capture as much solar heat as possible and insulate the enclosure well to keep the heat in.

Passive solar building design is an important means for slowing climate change by reducing the burning of fossil fuels. It is not, however, a least first-cost way to build. Larger, better insulating windows or opaque collector constructions cost more than conventional constructions. Three arguments justifying this investment are:

– Long-term (>10 years) good return on the investment
– Economy and security as future fossil fuel prices increase and supply subject to interruptions
– Living qualities of passive solar buildings flooded with light and natural warmth (Fig. 1)

Introduction

Concepts

Buildings that consume less fossil fuel are "nice to have" today, but will be essential in the future. Since buildings are long-term investments, they must be built or rebuilt looking to the future.

Heating is a major use of energy in buildings and dependence on fossil fuels for heating can be dramatically reduced through two strategies: reducing heat loses and increasing the use of solar heat. Logically, a combination of these two strategies is desirable.

Solar energy can be used by passive or active means:

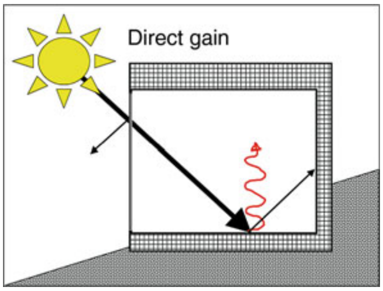
– *Passive solar use* does not rely on mechanical components to capture, store, and distribute the heat, the building construction fulfills these functions.
– *Active solar use* typically involves a remote solar collector and a pump or fan to transfer the heat to storage and from storage to point of use.

A low energy building must lose as little heat as possible, hence the importance given to insulation, air tightness, and heat recovery. An example design standard promoting extreme energy conservation is the "Passive House Standard" [1]. To meet this standard in Europe, three requirements must be fulfilled:

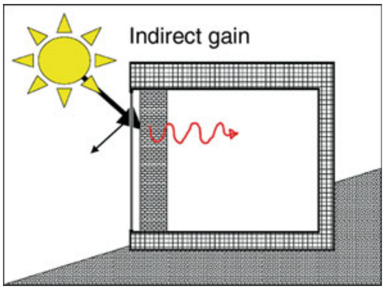
– The annual heating requirement must be less than 15 kWh/(m^2a) or maximum heating power 10 W/m^2a based on the net heated floor area.
– The combined primary energy consumption for heating, hot water and household electricity may not exceed 120 kWh/(m^2a).
– The air leakage of the enclosure tested under a pressured difference of 50 Pa (n_{50}) may not exceed 0.6 house air volumes per hour.

A passive solar building is not defined to this extent; it simply describes a structure in which the designer deliberately maximized using solar energy passively. So, in fact, a passive house can also be a passive solar house and indeed, in the planning recommendation for a passive house, using passive solar energy is encouraged and credited.

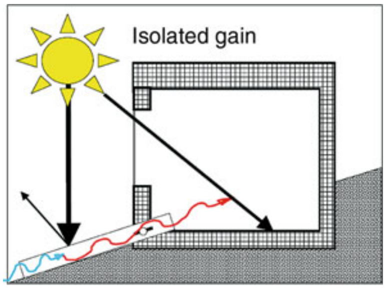
Three passive solar heating concepts were defined after the first oil shock of 1973 and are still useful today:



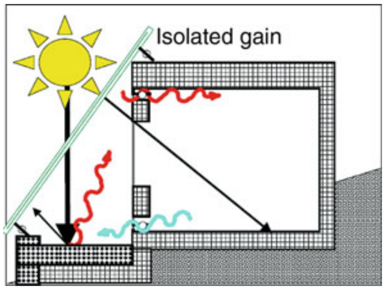
Direct gain: Windows capture the sun in a well-insulated building; interior construction mass stores the potentially excess daytime gains into the night; and some form of shading provides comfort during non-heating seasons. Direct gain is the oldest and still most cost-effective concept, given its potential to also enhancing the quality of life in buildings.



Indirect gain: The building envelope captures solar heat, which is then conducted and/or convected to the building interior, possibly with a time delay of up to 8 h. Alternatively, the goal may be simply to capture enough solar heat in the envelope construction to eliminate heat losses from the building much of the time, i.e., a dynamic *U*-value over the heating season approaching zero. Indirect gain systems nicely compliment direct gain systems.



Isolated gain passive: Solar energy is converted to heat outside the insulated building envelope and then deliverd to the building interior or storage. This can be by gravity-driven convection, or with the help of a small fan (a "hybrid" system). While not purely passive, hybrid systems are reported here because the proportion of delivered heat to electrical energy is so small.



A sunspace or attached greenhouse with controlled opening to the building is also an isolated gain system. Isolated gain systems are the most complex and expensive, but offer the most control of when and how much solar heat is delivered into the building.

It can be useful to consider passive solar heating opportunities by building types and climates. Note, that in this section, locations north of the equator are assumed. South of the equator, north orientations have priority.

Building Types

Buildings where heating loads dominate over cooling loads are the obvious candidates for passive solar design, i.e., residential buildings and small commercial or institutional buildings. Three factors are decisive here:

- As the ratio of enclosing surface to enclosed volume increases, heat loss increases, so a solar heating can be more beneficial.
- As the density of heat production from people or appliances increases, the usefulness of solar heat decreases.
- Direct solar gains in the form of heat and light are a combined asset, i.e., for hospitals, old age homes, and schools as well as residences. (Examples and Design insights for passive solar use in commercial and institutional buildings were researched and documented in an IEA project [2].

The energy optimization of a building must balance passive solar and daylight benefits against mechanical cooling and electric lighting energy demands, both of which have very high primary energy factors.

Climates

Northern climates such as Scandinavia would seem to pose a problem for passive solar use. Winter days are short, the sun is weak, and the sun path is at a very low angle. This means, however, that windows or vertical collection surfaces intercept the sun at a more direct angle. Furthermore, the heating season is very long, extending from early autumn to late spring. Before 21 September or after 21 March, heating is still needed, when days are longer than in southern latitudes. Passive solar concepts must maximize the usefulness of spring and autumn solar heating, while minimizing mid-winter heat losses.

Temperate climates are the ideal situation for passive solar buildings. Not just sunny temperate, but also overcast temperate climates. This has become possible with the development of very high-performance glass (U-value < 1.0 W/m^{2}K). Consider the example of diffuse solar radiation at only 100 W/m^2 for 6 h and an ambient temperature of 5°C. The solar gains through a glass with a g-value of 0.5 (admitting 50% of the solar radiation) will offset the 24 h heat losses of a glass with a U_{glass} of 0.8 W/m^{2}K. If the sun shines with more intensity or more hours, it is a passive solar winner. Because temperate climates often have hot summers, the concept must also include shading.

Mild climates offer a challenge: to achieve zero-heating energy buildings by combining passive solar design and conservation without degrading summer comfort. This is at least as challenging as achieving net-zero-energy buildings. The latter achieve a net zero balance by taking a credit from the summer electrical output of a large PV-roof (multiplied by a high primary energy factor) against the energy deficit in winter, which must somehow be met. Passive solar heating of a highly insulated building can answer part of the "somehow" question.

Strengths and Weaknesses

+	Living quality: daylight and naturally warmth from the sun's warmth.
+	Security: in the event of energy supply interruptions.
+	Costs: only the marginal costs of added aperture area, be it collector or window area and mass, must be amortized by energy savings.
+	Return on investment: As energy prices rise, return on the investment in passive solar measures increasingly attractive.
+	Low maintenance: There are no maintenance costs for pumps or fans.
+	All of these factors can positively affect resale value of the property.
–	Operation: often passive solar use requires active occupants adjusting sun-shading or opening windows or vents.
–	Poorly designed or incorrectly used passive solar buildings may use more energy than conventional buildings. Informed design, strict quality control, and intelligent operation are essential.

Road Map to This Section

A historic review of passive solar design shows how this approach has developed in parallel with technological developments of building components. It is instructive to examine which concepts came into existence, evolved, flourished, or died out. This may save reinventing a broken wheel, or ideas might arise for new variations or concepts.

Principles and applications review different approaches to passively capturing, storing, and using solar energy to heat buildings.

Direct, indirect, and isolated gain concepts are reported in detail.

Finally, the past, present, and future of passive solar heating are discussed in the context of expected energy supply developments, demographics, and increasingly well-insulated and automated buildings.

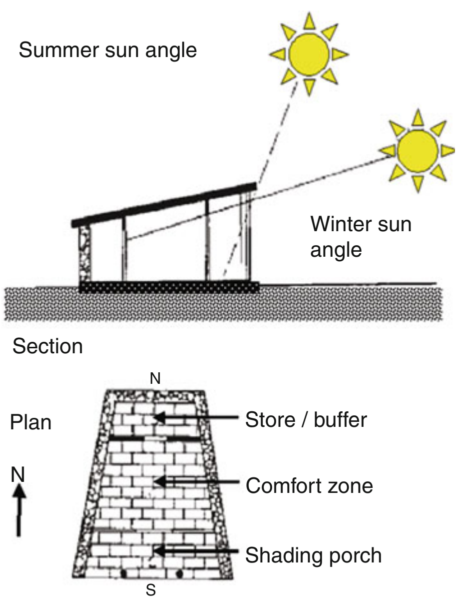
History

Concepts for passive solar heating date back millennia. Materials and components were very primitive by today's standards, but comfort expectations were also much lower. A net solar gain is possible even with single glazing if the required room temperature is only 16°C. The twentieth century saw dramatic developments in material science and production techniques, e.g., in glass production. The evolution in the last century has been equally spectacular. Single glazing at the beginning of the twentieth century ($U = 5.8$ W/m^{2}K), evolved to fused double glazing in the 1950s ($U = 2.8$ W/m^{2}K). Insulating glazing ($U = 1.2$ W/m^{2}K) in the 1990s is now available in triple glazing ($U = 0.5$ W/m^{2}K), or more than a factor 10 better than window glazing a century ago.

As a result, some concepts, which earlier proved ineffective for a given climate or building type, may indeed be effective today and should be "rediscovered." Following is a short-time journey through the evolution of passive solar heating.

Ancient times

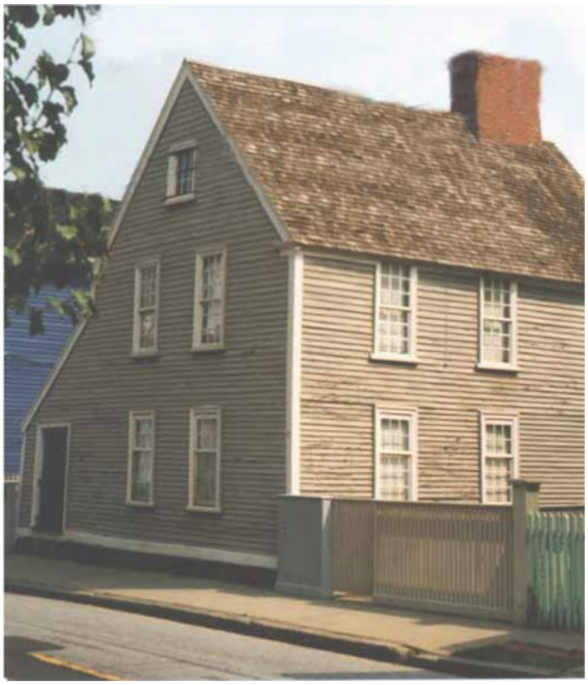
The most often cited example of awareness of passive solar use is a concept house, the "Megaron House" (Fig. 2) described by Socrates (469–397 B.C.). He expressed the following thoughts: "Doesn't the sun shine into houses facing south in winter, whereas in summer the sun wanders over us and the roof so that we have shade? Because this is comfortable, then south-oriented rooms should be built higher in order not to shut out the sun, whereas the north rooms should be lower because of the cold north wind." This was the logic for this funnel-shaped house concept, opening in plan and section to the south. A roofed porch admitted sunlight into the main room in winter but shaded it in summer. A room to the north served as both storage and as a buffer from the north exposure.



Passive Solar Heating in Built Environment. Figure 2
The Megaron House concept described by Socrates

1600–1900

New England Salt Box: A classic passive solar house form appeared between 1650 and 1830 in New England, the "Salt Box" (Fig. 3). Its name is derived from the shape of boxes used to store salt at that time. Initially, the house form came about when an addition was made to the rear and the roof slope carried down from the two-story main house. Typically, the addition incorporated a kitchen with its own fireplace, a pantry, and a room for child birth or nursing the ill [3]. The



Passive Solar Heating in Built Environment. Figure 3
A New England "salt box" house with large south façade and long protecting roof to the north (photo source: robert.hastings@aeu.ch)

Passive Solar Heating in Built Environment. Figure 4 An Appenzell house with large window area protected by multiple roof projections (photo: robert.hastings@aeu.ch)

main chimney rose inside the house to keep its heat inside. Also, very practical are the double-hung windows. The sashes were hung on ropes with counterweights of iron or bricks in a cavity of the window frame. The upper sash could be lowered and/or the lower sash raised independently. The height difference between the upper and lower openings induced air circulation.

Swiss Appenzell House: The Swiss Appenzell houses from the eighteenth to early nineteenth century had facades with many window bands protected by a projecting roof at each storey (Fig. 4). This afforded summer shading and weather protection for the windows. The curved white under surfaces captured and deflected additional daylight down to the windows.

1900–1950s

In The year 1927 saw a breakthrough in glass production. Using the Penn vernon Drawing Machine, glass was pulled through rollers in a new process implemented by PPG Industries. For the first time, large sheets of glass could be produced. This opened exciting new architectural possibilities, but with large heat losses and comfort problems. With the introduction of insulating glass by LOF, it was possible to have large window areas and net solar heat gains. Architects played with the design opportunities this new technology offered. Researchers quantified how long a room could be kept warm by what outside conditions. The press publicized what was then possible with new solar houses. Solar buildings were a mainstream topic. An example of such architecture is the work of the Architect George Fred Keck. Figure 5 shows the living room with a stone floor and fireplace to absorb the sunlight flooding in from the full southwest front of windows [4]. This house, built for Dr. and Mrs. Hugh Duncan of Flossmore, IL, United States, was monitored by two researchers. The performance was surprisingly good. One winter day in 1941, when the ambient temperature was −20°C, the heating system shut off by 08:30 h and stayed off until 20:30 h [5].

Passive Solar Heating in Built Environment. Figure 5 Direct gain maximized in the Duncan House (picture by permission of Pilkington, North America, Inc.)

1960s

Oil was plentiful and cheap, everyone was happy, renewable energy was not a topic of any popular importance and very little happened.

1970–1980s

In 1973, an oil embargo imposed on the United States led to a crisis of historic proportions. Americans can react astonishingly effectively and quickly to a crisis and this was the case then: "overnight," a national program to reduce foreign oil dependency was initiated. The Energy Research and Development Administration (ERDA) was activated on 19 January 1975 and the Solar Energy Research Institute (SERI) in Golden CO was founded. The department of Housing and Urban Development (HUD) held a national competition with grants for building the solar houses. Many built projects were monitored by national laboratories and published [6], as, for example, the Balcomb house shown in Fig. 6. In 1977, the first National Passive Solar conference was held [7] and in subsequent years, each conference drew over a 1,000 enthusiasts.

Passive solar use was a major topic of the American Solar Energy Society (ASES), a national organization linked with the International Solar Energy Society (ISES). These were the boom years for passive solar buildings. Research and demonstration projects were well funded at the federal and state levels. Atomic physicists "saw the light" and became solar building physicists at renowned national laboratories, including Los Alamos, Lawrence Berkeley, Brookhaven, and the National Bureau of Standards. Exemplary demonstration projects were sponsored by the Tennessee Valley Authority (TVA), an enormous interstate electrical utility. Regional solar energy centers oversaw the evaluation and publicizing of countless solar buildings.

Passive Solar Heating in Built Environment. Figure 6
The Balcomb house in New Mexico (photo source: robert.hastings@aeu.ch)

To help energy consultants, researchers, and academics analyze concepts, complex computer models were developed. These could quantify the dynamics of solar and heating input, heat storage, and building heat losses. Auxiliary heat demand and comfort performance were reported on an hourly basis. These tools were, however, difficult to use. Input was cumbersome and errors easily made. Computers in the 1970s still had to be "spoken to" via punched cards. The input was in rows of numbers, separated by spaces or commas punched into cards. Examples of programs include DEROB, NBSLD and BLAST, and later, DOE2. To provide design consultants (designers couldn't compute) with calculation tools, two approaches were followed:

– Gigantic data bases were computed using research computer models for all thinkable design variations, and then clever nomographs generated. The Passive Solar Handbook by Doug Balcomb and R. Jones is a classic example [8].
– Simplified calculation tools were programmed, such as SERIRES (later called SUNREL) and CALPAS. These were small enough to run on the first versions of portable computers ("mini" or "midi" computers).

The goal was to learn how sensitive performance was to a given parameter. To demonstrate how terrific a design was, it was useful to compare it to a conventional builder house of the time. For this purpose three reference houses were defined, based on statistics from the national home builders association (NHBA). The reference designs were published by the National Bureau of Standards (NBS, today NIST) [9].

To be sure, the computer models were telling the truth, measurement data from components and even whole buildings were essential. Test cabins for monitoring systems became a common sight at many national research facilities. Figure 7 shows a test house with an interchangeable modular south façade and clerestory windows sun lighting the north rooms.

Meanwhile at universities, architecture schools continued to teach Le Corbusier as the model for good design. Energy and solar use were not significant design issues, with the exceptions of a small but growing

Passive Solar Heating in Built Environment. Figure 7 NBS (NIST) test house 1980, Gaithersburg, MD (architect and photo source: robert.hastings@aeu.ch)

number of architecture and engineering professors. They were the authors of some superb text books, which clearly presented passive solar design principles. Some examples are a passive solar textbook for architects [10], a guide for adapting solar concepts to regional climates and constructions across the whole continent [11], and guidelines for window design strategies to conserve energy [12].

During this period, there were a few good examples of passive solar innovation in Europe as well. The Michelle–Trombe Wall concept was a notable example (Fig. 8). The original pilot building was constructed at the Centre National de la Rescherche Scientifique (CNRS) in 1967 in the south of France and further developed with a vented version of the wall in 1974 [13].

Passive Solar Heating in Built Environment. Figure 8 The Michel–Trombe wall house in Odello, FR (photo: robert.hastings@aeu.ch)

1990s

Europeans began to take interest in the American passive solar movement. Many architects and building researchers travelled to the United States to personally visit passive solar houses. Passive houses began to appear across Europe, from Scandinavia to Italy. National research programs investigated how to optimize passive solar concepts to local European climates and constructions. This was essential. Several passive solar buildings did not function as hoped. Europe gets less sun than New Mexico!

During this time, windows were still mostly double glazed or at best triple glazed ($U_{glass}=3.0$ or 2.2 W/m^2K). Glazing with selective coatings and noble gas fillings were just beginning to enter the market. Accordingly, only windows facing south achieved a net passive solar gain. In northern climates, night insulation of windows was needed for the long dark winters. Several innovative, but expensive roll-down insulating blankets were developed for windows. These largely disappeared from the market as high-performance glazings appeared.

By the end of the 1990s, the growing pains of adapting passive solar architecture to European climates and constructions were over and countless exemplary projects had been built and published. An IEA SHC program searched out and documented exemplary projects [14].

2000

During this period, many conventional passive solar-heated houses were built across Europe. Sunspaces were a favored architectural element. Many houses included active solar systems to heat domestic hot water, with

Passive Solar Heating in Built Environment. Figure 9 An Austrian passive solar house with solar air radiant heating and a sunspace in Nüziders, Vorarlberg (architect and photo source: Sture Larsen, www.solarsen.com)

Austria leading in the number of such houses. European architects often succeeded in adapting passive solar house designs into good architecture. An example project from 1992 by a Norwegian architect practicing in Austria, Sture Larsen is shown in Fig. 9 [15]. The exterior of the house is in light, wooden framing, the interior is in massive construction. Solar heated air is circulated through the walls and floors to radiate into the rooms. A sunspace also helps heat the house.

By the year 2000, a new concept, The Passivhaus (Passive House) had become well established and on the way to becoming the new mark of excellence in low-energy design. It came out of the PHD work of Wolfgang Feist under his Professor, Bo Adamson in Sweden. To reach this standard requires a highly insulated, thermal bridge-free, and airtight building enclosure. Mechanical ventilation is needed to assure good air quality by such tight construction. Heat from exhaust air is then recovered to preheat incoming air. The ventilation air can be used to deliver the small amount of heating needed (maximum 15 kWh/m^2 heated floor area). Obviously, passive solar heating of such houses is also desired, but challenging to dimension because of the small heating load and short heating season.

2010

Today, in the second decade of the new millennium, the term "passive solar heating" is less common. This is paradoxical because with new window frame and glazing systems, highly insulated building envelopes, and sophisticated heating control systems, passive solar gains can cover all heating needs for an extended part of the year in temperate climates. However, the interaction between passive solar gains, internal gains and envelope heat loss needs to be carefully studied to assure comfort and the hope for energy savings.

The former research computer models to study passive solar building concepts, requiring several hours on a main frame computer, today can run in seconds on a laptop. However, today's tools do not consider many of the phenomena the former models did, such as when mass is directly sunlit or only indirectly warmed by room air, or how passive solar heat in south rooms convects to other rooms. This can strongly affect passive solar usability and comfort.

Principles, Applications, and Integration

Principles

Passive solar heating requires glass, frames, seasonal sun shading, mass, and extra planning effort. The economics are clear: energy won is more expensive than the energy saved by adding insulation or eliminating air leakage up to a certain point. However, as the insulation thickness is increased, the marginal energy and economic benefits of the next increment decrease. Further, when conventional thicknesses are exceeded, the costs of anchoring the insulation and detailing jump. In contrast to this, the cost of a larger window is not proportional to the window area increase. Larger windows loose less heat per unit area. There is less perimeter for the glass area, so edge losses are smaller. Also, there are increased benefits such as more daylight, the view outside and sense of well being from being sun-warmed (especially for cats). The challenging questions are therefore, which passive solar heating concept is most effective for a given building type and climate, and how big should the system be?

Applications by Building Types

Well-Suited Building Types *Residences* are the most common passive solar application. Detached single-family houses with four outside walls, a roof, and earth contact can best benefit from passive solar gains. Row houses and apartment buildings have many units with only two exposures. If they face east and west, passive solar heating is difficult. One idea would be to install an indirect gain system on the south-facing end walls to compliment morning and afternoon direct gains.

Large buildings suitable for passive solar indirect heating include warehouses, gyms (American), or athletic halls (i.e., tennis halls) [2]. Because a lower air temperature is acceptable or even desired, passive solar gains can make a greater contribution to meeting the heating demand. Heat losses of glazed areas decrease proportionately with less inside to outside temperature difference. Lower required space temperatures increase system efficiency and number of hours when useful passive solar heat can be delivered.

Swimming pool halls are a potentially good building type for passive solar heating because a high air temperature is needed, so there is a very long heating season, well into long day spring and fall seasons. Also, there is a great appeal for the space being sunlit. Direct gain, indirect gain for radiant comfort, and isolated solar air systems for humidity control are possibilities.

Limited Cases *School* class rooms have high internal gains and high ventilation requirements. The benefit of passive solar heating occurs primarily during heating season weekends and holidays. At that time, typically there is a temperature set back and temperature swings are tolerated, maximizing the usability of passive solar gains. The obvious choice is direct gain with daylighting within the constraints of glare control, thermal comfort near the windows, and the view out being more interesting than the view to the front. Isolated passive solar heating is another alternative. Figure 10 shows a Swiss school with glazed-in balconies off the classrooms. Sunspace heated air preheats incoming ventilation air over a heat exchanger for the classrooms [16].

Old-age homes, nursing homes, and hospitals can benefit especially from direct gain with daylighting. Indirect gains systems to supply heat at night or isolated gain systems to preheat ventilation supply air are further possibilities. The occupancy tends to be “24/7” and demand somewhat higher room temperatures, extending the heating season.

Passive Solar Heating in Built Environment. Figure 10 A Swiss school in Gumpenwiese ZH with sunspaces tied into the ventilation concept [16] (photo: robert.hastings@aeu.ch)

Hotels have a transient occupancy. Guest rooms may be vacant with no internal loads for heating, but must be kept at room temperature or, if the thermostat is set back, very quickly warmed up. Accordingly, passive solar gains to maintain a minimal room temperature can be very useful, but mass can slow the heat-up. Daylight and view out may be assets, but overheating is totally unacceptable. Hotels in cities often may have to be isolated from traffic or airport noise. This can be solved with acoustical glazing or by using an indirect or isolated passive solar concept.

New Construction Verses Renovation *New construction* should have very low energy demand as a result of very good insulation, mechanical ventilation with heat recovery. They likely will have a sophisticated heat production, delivery, and control system. Therefore, internal heat from occupancy and appliances will maintain the desired room temperature later in autumn and earlier in spring. The design of passive solar heating must consider this shorter heating season. Storing solar heat is very important because the gains can quickly exceed demand and result in overheating. Ideally, the thermal mass should be sunlit directly. Indirect passive solar systems can contribute to helping shorten the heating season.

Renovation is an excellent opportunity to increase passive solar heating. Older buildings have a greater and longer heating demand than well-done new

Passive Solar Heating in Built Environment. Figure 11 Renovation with solar and conservation, 60 examples of projects across Europe and Canada [17]

structures. The subject of renovating existing housing was studied in a 4 year project of the Solar Heating and Cooling Program (SHC) of the International Energy Agency (IEA). As part of this work, 60 exemplary projects and an overview with insights were documented in brochures and are available on the Internet (Fig. 11) [17]. Included are apartment buildings, row houses, and single-family houses as well as the special case of historic buildings. The examples come from 10 countries: AT, BE, CA, CH, DE, DK, I, NL, NO, and SE.

Inappropriate Building Types Since the sun shines during the daytime, all buildings that do not need heat during the day are not good candidates. Large office buildings, shopping centers, airport terminals are examples of inappropriate building types. Such buildings must cope with energy-intensive cooling problems.

Applications by Climate

The best climates for passive solar heating buildings are climates that are sunny (so there is energy available) and cold (so there is heat demand). Buildings located at high elevations often have both sun and long heating seasons, which is ideal for passive solar heating. Not surprisingly, there are many good examples of buildings in alpine regions in Europe or the Rocky Mountains in the United States. The absolute best climate for passive solar heating is the southwest of the United States, which is why the passive solar renaissance after the oil shock began there. A very good tool for generating climate data to analyze systems is Meteonorm [18].

Cold climates in northern regions have short days in mid-winter. This disadvantage is somewhat offset by the heating season beginning before the autumn equinox and extending past the spring equinox. At those times, days are longer than in more southern latitudes. A further help is that, due to the low sun path, windows or wall collectors intercept sunrays more directly.

Temperate climates are well suited for all types of passive solar heating, as is evidenced by the many examples in temperate regions of North America and Europe. In overcast, temperate climates, direct gains systems can profit from even diffuse solar gains, given the highly insulating glass available today.

Mild climates pose the challenge to achieve zero heating energy performance through conservation and passive solar measures. Paradoxically, people in mild and sunny climates have the least interest in passive solar design. This is perhaps due to priority being given to passive cooling.

Dry climates generally have very good solar availability and large day–night temperature swings. Passive solar heating with mass for storage can be very effective.

Humid climates are a problem for both passive solar heating and natural cooling. Humidity reduces solar intensity, day–night ambient temperature swings and blocks night sky radiation for natural cooling. Humid climates are difficult.

Architectural Integration

Direct gain, indirect gain, and isolated gain are simple concepts; the challenge is to translate a diagram into architecture. The aesthetics of solar design is interesting to observe historically.

Before the twentieth century, building glass was expensive. In some cities, windows were even taxed. Because of their value, they were carefully and

Passive Solar Heating in Built Environment. Figure 12 Classical and "modern" fenestration of facades, two contrasting buildings in Pilsen CR (photo source: robert.hastings@aeu.ch)

artistically integrated into a façade design. Baroque facades are a beautiful example of the celebration of windows, in contrast to the austere holes punched in "contemporary" buildings, as can be seen in a street photo taken in Pilsen CR (Fig. 12).

Early twentieth century architects could play with large glass formats for the first time, but the resulting architecture, while making history books, often resulted in buildings that were an energy disaster.

After the oil shock of 1973 passive solar design (post oil shock), an epoch of innovation and experimentation, both technically and also aesthetically, began. The aesthetics varied greatly, from "California hippy" and New Mexico oil drum to developer Colonial Style. Inventors developed movable reflectors to concentrate sunlight on passive solar elements and movable shading systems for overheat protection. Also, thermal mass became a design opportunity, with glass blocks filled with colored water, glazing filled with phase change material, and rock bins as standing wall elements. Many components were used before they were technically mature. As a result, some components disappeared as quickly as they had appeared, and a design aesthetic never really matured.

By the end of the twentieth century, only technically and economically viable passive solar heating concepts remained. In Europe, the aesthetics of passive solar architecture profited from the attention given to detailing and superb craftsmanship. Design also suffered, however, from the box form architecture which became a craze and results in sterile, boring cubes. Name architects began to apply such concepts, wanting to profit from the growing environmental awareness. North American architects shifted to green architecture, with an emphasis on use of natural material and renewable energy in environmentally benign designs. The best examples are corporate offices and local institutional buildings from schools to park headquarters.

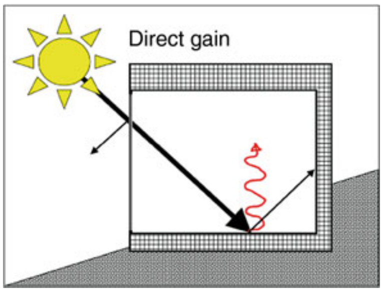
In the twenty-first century, the focus is on conservation. Manufacturers have responded to demand from Passive House planners, so there are now very good components on the market. An example is the windows, now available with a combined *U*-value (frame and glazing) of 0.8 W/m^2K.

The aesthetic integration of passive solar, active solar, and photovoltaic (PV) systems is still evolving. Too often, the engineering may be excellent but the resulting appearance not, or vice versa. First semester architectural design principles are also valid for solar systems integration. The resulting "design" should please laymen and not just editors of high-end architecture journals. These concerns were discussed in a session of the Passivhaus conference in Krems AT [19].

Following is a presentation of the three passive solar heating concepts and their variations with example built projects, hopefully which appeal also as "designs."

Direct Gain

Principles



Windows transmit sunlight into the building interior where it is absorbed, and becomes heat. The windows trap the heat in the room and interior construction mass stores some of the heat for the night.

How well the glass transmits solar energy is characterized by its g_{value}. A value of 100% would mean all the solar energy gets through the window, i.e., when the window is open. Otherwise, the glass absorbs some of the radiation and is warmed. The warmth is radiated to the ambient and into the room. Since the ambient in winter is colder than the room, it receives more of that heat. Still, some of the heat absorbed in the glass is radiated into the room. That heat plus solar energy transmitted through the glass comprise the total solar gain. This sum divided by the amount of solar radiation striking the window is the *g*-value. Multiple pane glazing systems with selective coating drastically reduce heat loss, but also let less solar radiation into the room. However, the benefit of the lesser heat loss overweighs the reduced solar transmission.

The usefulness of passive solar gains depends strongly on the match or mismatch of solar intensity, occupancy heat gains, and heating demand over the course of a day. Table 1 summarizes characteristics of different window orientations.

Advantages and disadvantages of direct gain:

+	Simplicity	Window construction is highly developed with a long history of passive solar heating experience.
+	Efficiency	Mid-winter solar usability can approach 100%.
+	Economy	People need daylight; buildings need windows, so only marginal cost for better, larger windows must be amortized by energy savings.
+	Aesthetics	Light and warmth from the sun are assets. Fenestration strongly defines the “personality” of a building, hopefully linked to functionality.
–	Overheating	Risk greater than a windowless, mechanically cooled, and ventilated insulated cube. This risk, however, can be calculated and minimized and such a cube is no alternative for providing living quality.
–	Glare	Sunlight on a work surface, computer screen, or poster from Klimt is highly detrimental. Variable, occupant-adjusted shading is essential.

Passive Solar Heating in Built Environment. Table 1
Window orientations and characteristics

Orientation	Characteristic
South	Maximum usable winter solar gains. Easiest summer shading
West	Poor solar usability (solar gains follow all day occupancy gains). Overheating risk in summer. Shading more difficult (adjustable vertical elements)
East	Limited solar gains in winter, especially by morning fog. Good solar usability (solar gains after night set-back). Less overheating risk (no direct sunlight after mid-morning)
North	Least solar gains. Greater heat loss (colder microclimate of north side of bld.). Best, daylight orientation, least glare problem Ideal for offices, school class rooms. Good insulation glass required for comfort near windows
Tilted	Construction complicated, expensive. More difficult to keep weather and water-tight. Greater summer overheating risk (except tilted north). Mounting movable shading elements more difficult
Roof	Maximal daylight by overcast skies. Highest overheating risk (max. solar gains in summer). Difficult to shade. Greatest heat losses in winter accentuated by clear night sky radiation, minimal solar gains on flat roofs

Components

Glazing: Table 2 compares daylight transmission (*t*-value), solar transmission (*g*-value), and heat loss (*U*-values) for a sample of glazings [20]. Exact values are readily available from glass manufacturers’ catalogs. The first three glass types are seldom used today and serve here a reference for comparing modern glass.

Vacuum glazing: In multiple pane glazings, heat is transported by radiation between the panes and convection of the gas in the cavity between the glass panes. To improve performance, coatings are applied to the cavity side of the glass. The coating selectively lets more solar radiation through than heat back out. To reduce the convection heat loss, a noble gas, like Argon or Krypton, can be used. Their higher viscosity slows the convection loop. If there is no gas in the cavity, there can be no convection heat transfer. The only problems are to keep the atmospheric pressure from collapse, the glass panes together, and to maintain the vacuum. Small plastic pillars spaced evenly across the glazing area can keep the panes separated. Maintaining the vacuum is addressed in several patented edge sealing technologies. An important benefit of vacuum glazing is its slimness, with a total thickness of 6.5–11 mm depending on the needed glass strength. The gap for the vacuum is only about 0.25 mm. A vacuum between 4 and 10 Torr is used (a pressure unit equal to 1/760 of an atmosphere). This is a relatively weak vacuum; a thermos bottle has 6–10 Torr [21].

Glazing spacers in multiple-pane glazing are thermal bridges. Earlier insulating glazing used aluminum spacers. Unfortunately, aluminum is a good heat conductor, so edge losses were high. A next generation used stainless steel spacers, with a lower conductivity. Modern insulating glass units use spacers with a plastic thermal break. The improvement is substantial. Aluminum spacers have linear heat loss (Ψ) of 0.07–0.8 W/mK. The Ψ of a thermally separated spacer (i.e., stainless steel separated with plastic) can be as low as 0.04 W/mK. Table 3 illustrates how strongly the linear thermal bridging of the edge spacer affects the overall *U*-value of the glazing, depending on glass area [22].

Assumptions	U_{frame} = 1.6 W/(m^{2}K)
	U_{glass} = 1.1 W/(m^{2}K)
	Ψ = 0.070 W/(mK)

Passive Solar Heating in Built Environment. Table 2 Glass properties

Glass type	*t*-Value%	*g*-Value%	*U*-Value W/m^{2}K
Single 3 mm	90	85	5.8
Double	82	75	2.9
Triple	73	65	2.2
Double, low e, Argon	80	60	1.1
Triple, low e, noble gas	76	56	0.6
Double, low e, vacuum	68	50	1.2

Window frames are the weak thermal component of windows with highly insulating glass. The frame has a worse *U*-value and of course it blocks the sunlight. So, frames with a small profile are desirable. Frames with some form of thermal break to interrupt the heat path are desirable. Even the *U*-value of a solid wooden window must today be judged as optimal for very low energy buildings, as can be compared in Table 4. Note that, with the exception of the aluminum frames, good *U*-values can be obtained for all materials. Exact *U*-values should be obtained from manufacturers because the values given here can vary relative to specific products. Also, of course, insulation value is only one selection criteria among many, i.e., strength to resist wind forces, life span, and maintenance costs.

Fixed shading by roof overhangs is promoted as a solution for south facades. This must be questioned for climates with overcast winters. By an overcast sky, the most daylight comes from the zenith. Therefore, fixed overhangs block daylight during long gray

Passive Solar Heating in Built Environment. Table 3 U_{window} value of different windows sizes, including the effect of the edge spacer

w × h (mm × mm)	A_{window} (m^2)	Perimeter (m)	A_{window}/Perimeter	U_w (W/(m^2 K)
400 × 800	0.32	2,400	0.133	1.8
1,300 × 1,300	1.69	5,200	0.023	1.5
1,230 × 1,480	1.82	5,420	0.024	1.4
2,750 × 2,500	6.88	10,500	0.014	1.3

Passive Solar Heating in Built Environment. Table 4 Example window frame constructions and thermal properties

Frame construction	U_f frame (W/m^{2}K)
Solid wood[1]	1.3
Wood-aluminum[1]	1.2
Wood with air cavities[2]	1.1
Plastic[1]	1.1
Aluminum[3]	2.2
Aluminum with break[3]	0.9

[1]EgoKiefer, CH-9450 Altstätten SG, www.swiss-topwindows.ch
[2]Tischlerei Sigg GmbH, AT-6912 Hörbranz, www.passivhausfenster.at
[3]Schüco/Jansen AG, CH-9463 Oberriet, www.jansen.com

periods when daylight is most desired. For such climates, moveable shading is superior.

To estimate the adequacy of a south-facing overhang, the highest and lowest noon sun angles (21st June and December) are calculated as follows:

21 June	90° – latitude + 23.45°
21 December	90° – latitude – 23.45°

Taking Zurich (latitude approx. 47°N) as an example, the highest and lowest sun angles are 66.45°and 19.55°, respectively.

While this is a good first estimation for designing a shading geometry, the problem is that the sun has a lower angle before and after solar noon. An overhang should extend horizontally beyond either side of the window to give diagonal shading as the sun rises, falls, and moves laterally before and after noon.

East- and west-facing windows need vertical shading since at sunrise and sunset the sun will get under any overhang. Vertical shading elements that can be rotated away from the lateral movement of the sun are best, to allow shading and some view concurrently.

Mass increases the effectiveness of passive solar gains and is especially effective if directly sunlit (primary mass). It is up 150% more effective than secondary mass heated indirectly by the room air [10]. A recommendation for middle European-like climates is to provide 2,800 kg of mass per m^2 of window area [23]. Another recommendation is that for each m^2 of south-facing glass above 7% of the floor area, there should be between 6 and 8 m^2 of exposed thermal mass. An example would be a 200 m^2 house with 20 m^2 of south facing glazing. 6 m^2 of that glazing will require 36–48 m^2 of solar-exposed thermal mass [24]. Also, note for day–night heat storage, thickness greater than approximately 10 cm will not increase the sola usability.

If the primary mass, i.e., a stone floor or brick wall, is a dark color, it will absorb the solar radiation better, but the impact on daylight distribution must be considered. Light-colored sunlit surfaces, especially floors or side walls, are essential to diffuse daylight deeper into a room. Such surfaces should have a mat color to avoid glare.

How well a materials stores heat is indicated by its capacity. Table 5 gives the physical properties of some construction materials to compare their effectiveness as thermal storage [25].

An Example Building: A very impressive example of passive solar heating with windows is a single family house built at 900 m above sea level in Trin, CH. It has no auxiliary heating, not even a wood stove. The architect, Andrea G. Ruedi, matched a very large, south-facing window area (46 m^2), very plentiful mass inside the insulated envelope (Fig. 13). The envelope is wooden frame construction to simplify achieving a high insulation value (0.14 W/m^{2}K); the interior incorporates limestone bricks and concrete (see Table 6). The room temperatures were measured in a research project over the heating season, with no auxiliary heating. They varied between 18 and 23°C. Only very rarely did the temperature fall below 19°C. The theoretical annual heating energy, were 20°C maintained, was calculated to be less than 30 L of heating oil equivalent (1.1 kWh/m^{2}a) [26].

Design Advice

Maximize solar gains

- Orient direct-gain window gains between ±45° from south
- South window to façade ratio: 30–50%, not more
- Large, uninterrupted glass areas (to minimize frame and glass edge losses)

Passive Solar Heating in Built Environment. Table 5 Heat storage properties of common construction materials [25]

Material	Density ρ (kg/m^3)	Conductivity λ (W/mK)	Thermal capacity *c* (Wh/kgK)	Volumetric heat capacity Wh/m^3
Metamorphic stone	2,800	3.5	0.26	728
Sedimentary stone	2,600	2.3	0.22	572
Clay	1,700	0.9	0.24	408
Sand, gravel	1,800–2,000	0.7	0.22	418
Concrete reinforced	2,400	1.8	0.3	720
Concrete aerated	1,000	0.3–1.0	0.3	300
Interior plaster	1,400	0.7	0.26	364
Gypsum board	900	0.21	0.22	198
Wood (pine, fir)	450–500	0.14	0.55–0.66	287
Wood (oak)	700–800	0.21	0.55–0.66	454
Wood (fiber board)	800	0.17	0.7	560

Passive Solar Heating in Built Environment. Figure 13 Extreme example of a direct-gain house in Trin/CH with no auxiliary heating (architect Andrea Ruedi, CH-7000 Chur)

Passive Solar Heating in Built Environment. Table 6 Properties of the solar House in Trin CH

Properties	Trin solar house	A reference house
South window area	48 m^2, (8% frame)	28 m^2, (20% frame)
South-facing window to façade proportion	56%	33%
Interior storage mass	277 t	190 t
Wall construction	Exterior: insulated wooden frame, Interior: limestone masonry	15 cm limestone 30 cm cellulose insulation

- Window $U_{window} < 1.0$ W/m^2K (including frame) and a good *g*-value (>50%)
- Account for winter sun blockage by neighboring buildings, trees, terrain

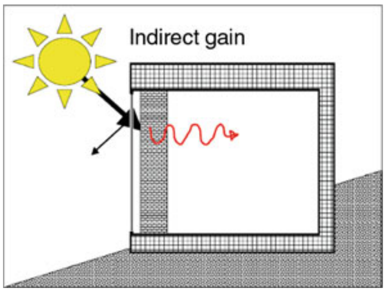
Maximize usefulness of passive solar gains

- Interior construction with adequate sunlit (primary) mass
- Room interior finishes light color to maximize light distribution
- Open floor plan. Largest rooms on south-side (small rooms overheat faster)
- Auxiliary heat control responsive to passive solar gains
- Shading elements: horizontal for south, vertical for east/west

- Adjustable shading to allow concurrent view and ventilation
- Exterior sun shading to keep absorbed heat outside
- Generous operable window area with max. height difference to induce natural ventilation (diurnal cooling where possible)

Indirect Gain

Principles



Sun warms building walls and roofs but normally the heat is radiated and convected back to the ambient. By protecting the surface behind glass, heat can be trapped within the construction, stored or transported into the building to reduce auxiliary heating demand.

Several variations of this concept have been built including: the mass wall, mass roofs, transparent insulation, and solar insulation. Of the many innovative concepts, only a few have survived into the present, but with rising energy prices and availability of new high-performance components, these concepts can be promising.

How much passive solar heat gains can reduce purchased heat demand depends on the intensity and timing of the sunlight, occupancy heat gains, and room temperatures desired. Table 7 summarizes characteristics of different window orientations.

Advantages and Disadvantages:

+	Simplicity	The concept is simple, some variations do not have any moving parts.
+	Aesthetics	Most systems include large glass areas, which can be integrated with window areas into an attractive transparent façade concept.
–	Inefficiency	Heat losses from the solar energy captured in the collector are radiated both to the inside and the ambient, reducing system efficiency.
+	Natural cooling	The chimney effect of an indirect gain system can draw cooler air from a ground channel or the north facade through the building for summer comfort.
–	Complexity	Many systems need seasonal shading to avoid summer overheating. Some require dampers to regulate and direct air flows.
–	Cost-benefit	Complex systems proved, in most cases, to be too expensive for the energy benefit.

Following are four variations of indirect gain systems, mass walls, mass roofs, transparent insulation, and solar insulation.

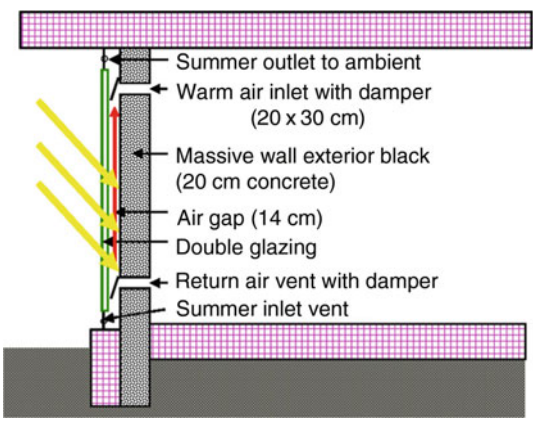
Mass Walls

A stone, concrete, brick, or adobe wall will absorb and store solar heat, but the heat is rapidly radiated and convected back to the ambient with little or no benefit to the heated building space. If the wall is protected behind glass, the heat is better retained. With a time delay, much of the heat can then penetrate and be radiated and convected to the room behind the wall (Fig. 14). This is the principle of the solar wall, patented in 1881 by Edward Morse, an American Botanist. In 1964, a French engineer, Felix Trombe and architect Jacques Michel built such a wall to demonstrate this principle. Since then, the mass wall or Michell–Trombe Wall has become popularly known as the Trombe Wall [27].

The wall has been built in two variations. In the unvented version, the wall delivers heat to the room only by conduction and then radiation from the wall surface, with up to an 8–10 h time delay, depending on how massive the wall is. In the vented version (Fig. 14), the vents open when the air in the cavity is sun-warmed. The air circulates into the room at the top of the wall and returns to the cavity through slots at the bottom. This variation delivers heat sooner so is better for east-facing walls, and would not be good for a west-facing wall. To prevent back circulation of cold air in the gap into the room at night, dampers are needed. One solution was a Mylar film damper, which simply flapped open or was pressed closed against a wire mesh by the air pressure. In summer, dampers could be opened at the top and bottom of the air gap to vent it

Passive Solar Heating in Built Environment. Table 7
Indirect gain system orientations and characteristics

Orientation	Characteristic
South	Maximum usable winter solar gains. Fixed overhang possible
West	Less solar gains compared to south-facing facades. Heat delivered to space at time of day when least needed, so storage important. Greatest risk of summer discomfort
East	Limited solar gains compared to south-facing facade. Less overheating risk (no direct sunlight after mid-morning). If storage included, heat delivered at mid-day when least needed
North	Least solar gains, questionable cost-benefit
Roof	Maximal night-sky cooling in summer, least benefit in winter. Steeper roofs intercept winter sun better



Passive Solar Heating in Built Environment. Figure 14
Concept of the Michel–Trombe mass wall

to the outside. Alternatively, only the top damper could be opened and a north window of the house opened. The chimney effect of the mass wall draws cooler air from the north side of the house, across the room and exhausts it out the top of the mass wall to the ambient.

The first project in Odeillo France (Fig. 15) was subsequently copied at Los Alamos, NM, United States, where it was instrumented and a computer model of its

Passive Solar Heating in Built Environment. Figure 15
The prototype Michel–Trombe wall house in Odeillo, FR (source: Robert.hastings@aeu.ch)

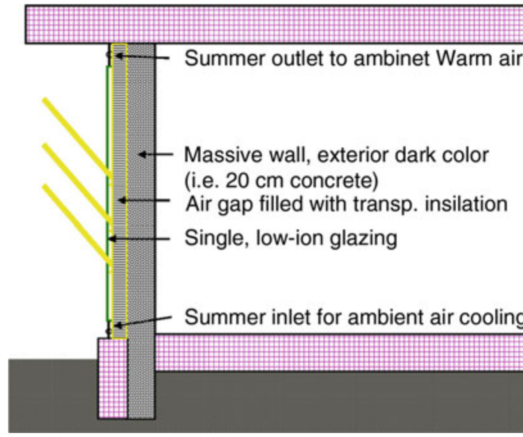
physics calibrated. Versions were then built in the 1980s in middle Europe. The performance during long, overcast winter periods was disappointing, while in summer the rooms behind the wall were too warm. Another solution was needed for this climate.

Mass Roof

An innovative alternative to a solar mass wall is a solar mass roof. It can provide both winter heating and summer cooling. One innovative concept uses a series of roof water bags (like a water bed) and moveable insulation panels. During the winter days, the insulation is slid back on its tracks, so that the water is sun-warmed. Nights, the insulation is rolled back over the water bags, which then conduct heat through the steel deck ceiling to be radiated down to the rooms beneath. In summer, the process is reversed. Nights the cover is removed and the water is cooled by radiation to the sky, days the insulation is slid in place and the rooms below are cooled by the cold water bags.

A prototype house was built in 1973 by the inventor of the concept, Harold R. Hay (Fig. 16). The three-bedroom, two-bath structure in Atascadero California was constructed and monitored with funding from the US department of HUD. It was the first documented 100% passive solar heated and cooled building and the only instrumented passive solar house in operation during the 1973 energy crisis. To engineer the system, the then new generation of computer simulation tools was used (simulations for this project done by

Passive Solar Heating in Built Environment. Figure 16
A mass roof: the Skytherm house in Atascadero California by Harold Hay (photo source: Evelyn and Harold Hay Fund at Cal Poly, San Luis Obispo, USA)



Passive Solar Heating in Built Environment. Figure 17
Transparent insulated wall concept

Phil Niles) [28]. It could be worthwhile to reexamine this concept, given the materials and insulation systems available today.

Transparent Insulation

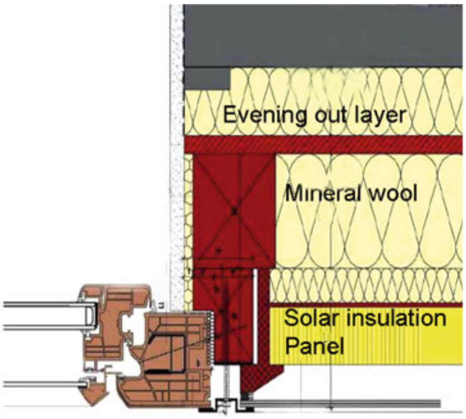
The transparent insulation wall (TWD) improved the performance of the mass wall concept by addressing one of its weaknesses. In the cavity, the air warmed by the black surface of the solar wall rises, while cooler air against the surface of the glass falls. The resulting circulation loop transports heat from the wall to the glass where it is then lost by conduction to the ambient. In the transparent insulation system, the air gap is filled with some form of transparent cellular structure, inhibiting the convective loop (Fig. 17). The infill material is typically a cylindrical, rectangular, or honeycomb geometry, which directs the light in multiple reflections to the mass wall at the back. A small vertical gap between the TWD and glass should be maintained, to allow moisture to diffuse and prevent the TWD from being in direct contact with the hot absorber surface.

In non-heating months, vents to the ambient can be opened at the top and bottom to the ambient to cool the wall. These proved to be difficult to keep air tight in winter and added cost. Some form of shading for the wall was needed. Window roller blinds are effective, but make the whole system prohibitively expensive. An innovative solution was to use fixed, metal micro louvers with the fins set at an angle to block high summer sun angles. They, unfortunately, also reduced winter solar performance and were expensive. A third variation uses fused transparent spheres 2–3 mm in diameter as the glazing, applied like transparent stucco. These let less solar energy through, but with the benefit of much better summer comfort behind the wall. The area of the glazing patches is for physical reasons limited [29].

Several transparent materials and geometries have been used to fill the air gap, including extruded PMMA-Capillaries or Polymethlymethacrylat (Plexiglas), extruded PC Polycarbonate (Makrolon) capillaries or honeycomb forms, and extruded polycarbonate multi-cell panels. Critical for the selection are the upper temperature tolerance and UV-stability. Some materials are stable up to 120°C, other to only 90°C. A good overview of products and properties is available from the association of TWD manufacturers [29].

A well-publicized example of a TWD-building under extreme conditions is a Swiss alpine hostel at Hundwiler Höhe at an elevation of 1′306 m above sea level (Fig. 18). It was built in 1995 and 42 m^2 of prefab TWD-Modules $130 \times 90 \times 18.5$ cm ($h \times w \times d$) were used. No summer solar protection was needed at this altitude. The 185 cm thick TWD wall construction (outside to inside) is as follows: 8 mm framing projection beyond the glass, 4 mm glass, 30 mm gap, 120 mm

Passive Solar Heating in Built Environment. Figure 18 Swiss TWD house at Hundwiler Höhe (architect and photo source: P. Dransfeld, www.dransfeld.ch)



Passive Solar Heating in Built Environment. Figure 19 Wall section of a cellulose solar wall insulation system (Redrawn based on a figure in the report: Domenig-Meisinger et al. [31])

transparent insulation, 8 mm absorber, 15 mm air gap between the absorber and wall. This air gap was needed to provide the needed tolerance for mounting the prefab TWD modules. The gap was estimated to cause a 10% reduction in efficiency, which was considered acceptable. Simulations indicated that the temperature in the TWD construction should not exceed 80–90°C, well within the 110°C tolerance of the TWD material used [30].

Solar Insulation

The solar wall concept is the simplest of the indirect gain systems and perhaps, therefore, most economical.

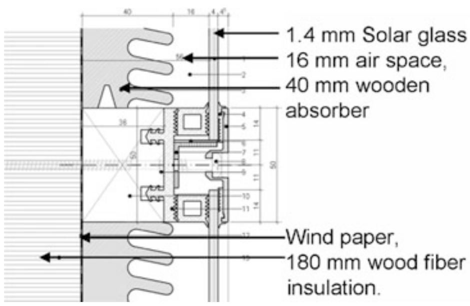
The goal of this concept is to provide dynamic wall insulation. During the day, air chambers in the cavity protected by glass are warmed by the sun. Nights, the cavity slowly cools down. The air chambers together with the glazing to the outside and insulation to the inside help reduce heat loss from the building.

Two construction variations exist for creating the insulating air chambers: a type of treated, corrugated cardboard and wood routed with horizontal slits.

The cellulose system (GAP), shown in Fig. 19, achieves on south facades a dynamic *U*-value of 0.08 W/mK in middle Europe [31].

A well-publicized example project using this concept is an Austrian Apartment building on Makartstraße, Linz (Fig. 20). To minimize disturbing the tenants, prefabricated wall panels including the solar walls, windows, sun-shading systems, and ventilation channels were mounted. The south facades achieve

Passive Solar Heating in Built Environment. Figure 20 Apartment building with the GAP solar insulation on Makartstraße, Linz AT (photo source: S. Grünewald and S. Rottensteiner)



Passive Solar Heating in Built Environment. Figure 21
A solar insulated wall detail of the routed wooden Lucido system (source: Lucido Solar AG Solares Bauen, www.lucido-solar.com)

a dynamic *U*-value of 0.08 W/mK averaged over the heating season. As a result of a combination of this wall system and other measures, the heating demand could be reduced by 92% to 13.4 kWh/m^{2}K [31] and [32].

The routed wooden system (Lucido) entraps air in inward-sloping slots (Fig. 21). Important in this and also the cellulose board system is that the wall behind the solar wall be well insulated. A benefit of the wooden absorber is that, being weather protected, it can be left natural and hence conveys the character of a wooden façade.

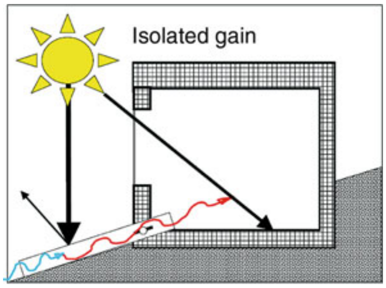
Design Advice

Following is design advice for temperate climates. In mild climates, these systems might make it possible to reduce auxiliary heating demand to zero, but summer comfort strategies must be well done. In a humid, hot climate, this system make no sense, nor is performance likely to be good in northern, very cold and weak-sun winter climates. Many projects were built in temperate climates but a market breakthrough has not yet occurred. The energy they save for the investment is high compared to energy from cheap fossil fuel.

- Because indirect solar gain is less efficient than direct gain, a large collection area is needed. South-facing orientations are most sensible. Depending on the desired timing of heat release, east- or west-facing solar mass walls are possible, but the absolute amount of delivered heat will be smaller.
- Overheating is a risk in mass wall systems, so summer sun shading and venting are important. The solar insulation concept has the comfort advantage of having an insulated wall separating it from the building interior.
- Durability was a problem for early prototypes, including untight vent dampers and degradation of sun-exposed wooden framing. A typical greenhouse construction with a metal cap to protect exterior wood is one solution. Transparent insulation can deform at high temperatures, so the right material must be chosen for the design, or reliable shading provided. Freeze protection UV-durable materials are obvious requirement for the roof-mass system using water.
- The thickness and density of a mass wall and hourly solar radiation should be calculated to dimension a mass wall to deliver its heat to the room when desired.
- System performance might be improved by very good insulating glass. This is a trade-off of *g*-value and *U*-value in the context of the economics. Single glazing in low-iron glass could still be the best solution (maximizing the *g*-value).
- The mass roof system is only plausible in clear-sky climates with both a heating and cooling demand.
- The room side of the mass wall or transparent insulation wall should not be blocked by furniture. For the solar insulation system, this is not an issue. The room surface of all the wall concepts can be any color desired.
- Prefabrication can provide cost savings for a second project, not necessarily the first project. The benefits are shorter on-site erection time, less disturbance of occupants, and better quality control, which can lead to better durability.
- Indirect gain systems are well suited for building renovations.
- These systems have gone through development pains; valuable experience is available from the project designers, research institutes, and the manufacturers of system solutions. Homework to assure a new project starts from the state-of-the-art is essential!

Isolated Gain/Hybrid

Principles



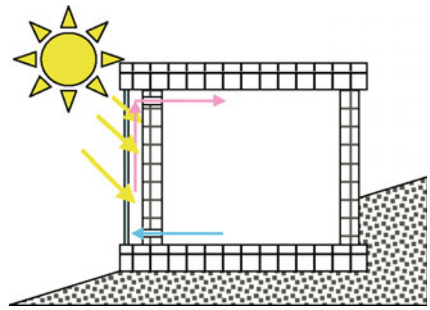
Solar energy is collected outside the insulated envelope of the building, then transported as heat by convection into the building or into storage. Two variations are considered here: solar air systems (with or without mass) and sunspaces.

The orientation of a sunspace, like any room, depends on view and when sunlight is wanted. For solar air systems, design issues are similar to those of indirect gain systems. Buildings uninhabited and kept at a minimum temperature much of the year (i.e., vacation homes) are an ideal application.

Advantages and disadvantages:

+	Simplicity	These systems are simple and reliable.
+	Dependability	The gravity-driven solar air systems work without moving parts. However, a small fan would improve the efficiency and can easily be PV-powered, making the system immune to grid power interruptions.
+	Economy	Reduced purchased energy costs and reduced wear from less running time of the auxiliary heating system, extending its lifetime.
+	Function	Sunspaces are built for the space they provide, energy savings are only a fringe benefit, so in effect a bonus.
+	Overheating	Isolated solar gains systems, because they are outside the insulated building, are advantageous regarding summer comfort. Sunspaces need large, low, and high ventilation openings, and effective shading and glare protection.
+	Natural cooling	The chimney effect of an isolated solar collector or sunspace can draw cooler air from a ground channel or the north facade through the building.

Solar Air Systems

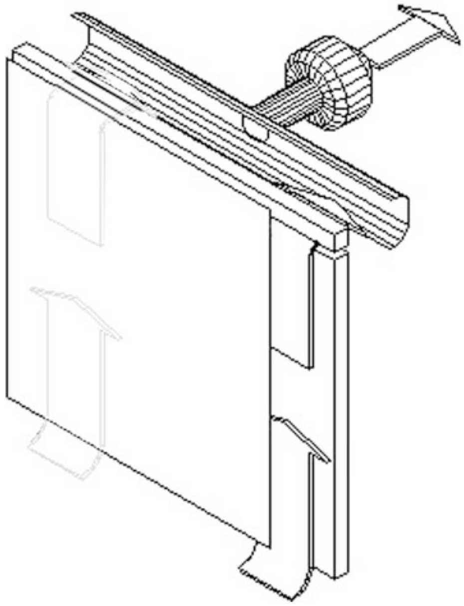


A solar air system is in effect a sunspace with the depth reduced to a few centimeters. The principle is the same as an active solar water system, except that heat is transported from the collector to the point of need or storage by air. Two variations are reviewed here: systems that are directly coupled to the building and systems in which the sun-warmed air passes through mass before entering the building. All together, six system types were researched in a project of the International Energy Agency. Out of this work, a design handbook for solar air systems [33] and a book of example built projects [34] were published. The other four system types typically require an electrical fan, dampers, and more complex control systems to function, so are not included here under passive systems.

No-Mass Solar Air Systems

These systems operate on the principle that sun-warmed air in a vertical or upward sloped volume behind glass will rise. This warm air can then be channeled through the insulated wall of a building to provide solar heating (Fig. 22). Two variations are possible for the air supply at the bottom of the collector:

– If the opening is to the ambient, the collector can deliver sun-warmed fresh air to the building.
– If the opening is to the building, the collector delivers recirculated, higher temperature air than



Passive Solar Heating in Built Environment. Figure 22 Diagram of a free convecting façade solar air collector

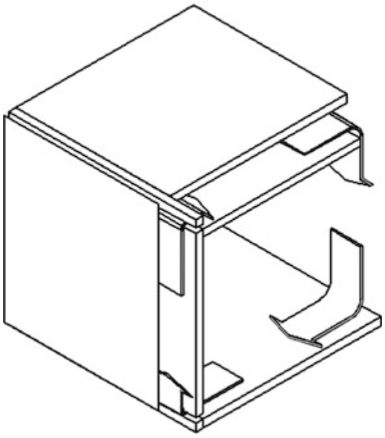
Passive Solar Heating in Built Environment. Figure 23 A solar air heater for a vacation home on a Greek island (photo and system information: www.grammer-solar-bau.de)

the first variation. In either configuration, in summer an outlet at the top can be opened to the ambient to exhaust the hot air.

Example: Figure 23 shows a solar air system to keep a vacation home in Koroni GR heated to a low level, ventilated and dry during periods of vacancy. Two collectors, each 6 m^2, circulate up to 200 m^3/h of fresh air into the house. A small PV panel (50 wp) integrated into a corner of the air collector powers a small fan to increase the efficiency of the system, which has been in operation since 2004.

Mass Solar Air Systems

This concept is like the no-mass solar air system described above, except that the solar-heated air circulates through the building structural mass before entering the room (Fig. 24). In this way, the air enters the room at not as high a temperature, and the mass continues to radiate the stored heat after sunset. The mass may be a concrete ceiling or floor (hypocaust) or walls (murocaust) with air channels. The system can function with only free convection of air movement [33].



Passive Solar Heating in Built Environment. Figure 24 A solar air collector linked to air channels in the building structure

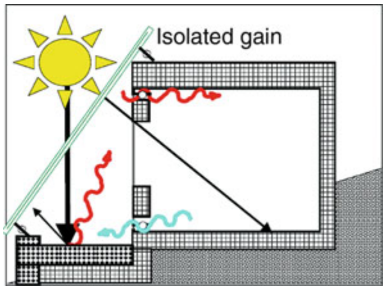
Example: Figure 25 shows an apartment building in Marostica, Italy (20 km from Vicenza) with a façade integrated passive solar air system. The sun-warmed air in the collector rises naturally and circulates though channels in the concrete ceiling/floor structure before entering the apartments in the north-facing rooms. The concept was developed by Barra-Costantini. Each 84 m^2apartment is heated by 16 m^2 of collector. Each m^2 of collector is estimated to contribute about 100 kWh/a [34].

Passive Solar Heating in Built Environment. Figure 25
Solar apartment buildings in Marostica by Barra Costantini (photo: Gianni Scudo)

Design Advice

- The collector can be mounted below floor level, i.e., in the case of a building with an above-grade basement. The height difference strengthens the free convection.
- No-mass solar air systems are well suited for buildings often vacant, which need to be tempered and supplied fresh air. In permanently occupied buildings, mass is essential to maximize the usefulness of the collector gains and avoid overheating.
- Dampers are essential to prevent reverse-flow and cooling of room air into the collector at night.
- A small fan can increase system efficiency. Commercial solar air systems with PV-powered fans are available.
- The collector and solar-heated air channeling require good engineering. Consult the literature to not have to reinvent the wheel [33, 34].

Sunspaces



Sunspaces became popular element of passive solar architecture. They were designed as an architectural feature which, in addition, reduced purchased energy consumption in several ways:

- Passively by creating a warm buffer zone on the south side of the house, reducing wall and window heat losses.
- Passively by occupants simply opening house windows and doors into the sunspace when its temperature exceeded the house temperature. Alternatively, a small thermostat could open a damper and switch on a fan to automate this.
- Actively, when sunspace supplied sun-warmed air to a mechanically ventilated building. Alternatively, the sunspace air could be ducted to a heat exchanger to warm incoming ventilation air for the building.

Today, in highly insulated buildings, a sunspace's buffering effect is no longer a significant energy saving. In mechanically ventilated buildings with heat recovery, the benefit of heating the incoming air is also less significant, but still a benefit. Sunspace heated air can exceed room temperature, thus supplying useful heat. A sunspace can increase purchased energy consumption if occupants heat it to near room temperatures. Comfort expectations of a sunspace must be less than for rooms.

Example: The Wydacker row houses in Zollikofen (Bern) CH are earth sheltered to the north and protected behind a sunspace to the south (Fig. 26). This construction provides energy benefits and protection from nearby street noise.

Each house has a 108 m^2 sunspace with a 57 m^2 of insulated glass (U=2.9 W/m^2K) at a 60° slope oriented 20° west of south. Being slightly west of south is beneficial. Frequent morning fog reduces solar radiation mornings compared to afternoons. Sun shading is provided by a roller shade beneath the glazing. The concrete block wall of the house and concrete pavers over gravel provide thermal mass for the sunspace. The measured heating energy consumption of the houses was 37 kWh/m^2a, which for the year 1995 was excellent performance [35].

Passive Solar Heating in Built Environment. Figure 26 Attached sunspaces as part of the concept of low energy row housing in Bern (Architects, AARPLAN; Bern, CH)

Design Advice

- Insulating glazing for both the sunspace (minimize freeze risk for plants) Insulating glazing for the house to minimize heat loss to the sunspace.
- Sunspace frame out of laminated wood to be dimensionally stable and metal exterior cap to reduce weathering. Alternatively, aluminum framing with a thermal break.
- Two or more story sunspaces offer d more collection area for the enclosed volume. Comfort is better because stack effect ventilation improves with stack height).
- Large operable sash at base of the sunspace and at its top, ideally with rain sensor-activated closers. Rule of thumb: Minimum1/6 glass area operable.
- Sun shading on exterior most effective, on interior it is less subject to wind damage and weathering. Interior sunshade installed min. 10 cm below glass so gap acts as thermal chimney between operable low inlet and high outlet sashes.
- As in direct gain systems, thermal mass helps reduce temperature swings (i.e., minimize hours below freezing.
- A freeze-protecting heater with thermostat activation when the sunspace temperature falls below 4°C can help protect plants. If the sunspace is designed, the purchased energy for this is well worth the plants.

Future Directions

The future directions to using passive solar energy can best be forecast by reviewing technical and political events in the past. In the early twentieth century, when production of glass in large formats became possible, architects began experimenting with large glazed areas. The resulting buildings were uncomfortable to occupy in winter and expensive to heat. First, with the introduction of insulating glass, a net passive solar heat gain in winter became possible. After World War II, oil became plentiful and cheap and interest in solar dwindled. Then, the oil crisis of 1973 renewed interest in finding alternatives to fossil fuels. New solar building concepts evolved under the collective term "passive solar heating." The first of annual "National Passive Solar Conference" was held in 1977 in Sante Fe, NM (United States) A US federal department (HUD) held a landmark national competition for innovative passive and active solar building concepts. Interest and built projects spread from the sunny southwestern United States across the entire continent. By the next decade, passive solar heating concepts were being applied by architects in Europe as well. Passive solar concepts, originating from inventive individuals, became a topic for national research institutions. Test cells and buildings were monitored, computer models developed, and engineering handbooks written.

Today, the term, "passive solar buildings" is less commonly heard. The similar sounding concept "Passive House" now enjoys international attention. The new, future-oriented trend is sustainable buildings [36, 37], net-zero-energy buildings, carbon neutral buildings, and even energy-plus buildings. Well-designed new buildings constructed to such high standards need very little heat, and so passive solar gains are less beneficial than before, but still an asset. Such solar gains help delay when the heating season finally begins and end the heating season earlier. Passive solar gains are also a major heat source when a building is unoccupied during the day or for extended periods. The daylighting aspect of direct solar gain concepts will continue in the future, being a major appealing factor.

Future buildings must address new requirements. There will be

– More elderly people (demographics) with greater comfort expectations.

– High energy prices, regardless whether the source is increasingly scarce fossil fuels, electricity, or renewable energy.
– Less disposable income because salary increases will not match the inflation of energy costs affecting prices of all goods and services.

New technological developments will offer new possibilities for meeting these requirements. Likely developments may include:

– Nanotechnology selective coatings for glazings to allow larger passive solar collection areas in winter and no overheating in summer. Similarly, material science will deliver high-performance coatings for absorber surfaces.
– Vacuum technologies for both window glazing and as very compact insulation for indirect or isolated gain systems.
– Intelligent, self-learning control systems for switchable property components, responding to solar intensity, ambient temperatures, and programmable occupant comfort profiles.
– Chemical thermal storage for heat or "cold" to provide very compact and high density, compact storage with no losses during storage.
– Building skins, which produce both electricity and low-temperature heat amplified by high-efficiency heat pumps for space and water heating.

Finally, in the future as in the past, political developments may result in supply interruptions. In any event, as the world-known reserves diminish, prices will not steadily and gradually increase. Large price swings amplified by speculation can be expected.

These changing occupant requirements, technical developments, and possible political and oil market events will change how new buildings are constructed and existing buildings renovated. They will more effectively draw energy from the environment, providing heat, light, and "cool" with less external energy input. Buildings and climate will no longer be combatants, but allies working together. The needed investment and maintenance costs will have to be low, simply because there will be less disposable income. Passive solar heating was, is, and will be an important strategy for achieving low-energy buildings offering excellent living quality.

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Rating Systems for Sustainability

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Article Outline

Glossary

Building Environmental Assessment Method (system or scheme) Technique that has environmental assessment as one of its core functions but may be accompanied by third party verification before issuing an overall performance rating or label.

Assessment process Use of assessment methods, including deployment by the design team and engagement of other stakeholders as the basis for making informed decisions.

Certification Third party verification and scrutiny of a performance assessment that adds to the overall credibility of the assessment process but invariably brings additional layers of constraints, bureaucracy, and costs.

Environmental (or green) assessment Assessment of resource use, ecological loadings, and indoor environmental quality.

Framework Organization or classification of environmental performance criteria in a structured manner with assigned points or weightings.

Rating (labeling) Extended output from the assessment process, typically in the form of a singular, easily recognizable designation, for example, "Gold" or "Excellent."

Sustainability assessment Assessment that expands the range of performance criteria to include social and economic considerations.

Weighting Assigning the relative significance of the environmental criteria to permit their aggregation into an overall single score.

Definition of the Subject

Voluntary building environmental assessment methods have emerged as a legitimate means to evaluate the performance of buildings across a broad range of environmental considerations – most typically resource use, ecological loadings, and indoor environmental quality. An underlying premise of these voluntary assessments is that if the market is provided with improved information and mechanisms, a discerning client group can and will provide leadership in environmental responsibility, and that others will follow suit to remain competitive.

The increase in development and application of building environmental assessment methods over the past 20 years has provided considerable theoretical and practical experience on their contribution in furthering environmentally responsible building practices. An important indirect benefit is that the broad range of issues incorporated in environmental assessments require greater communication and interaction between members of the design team and various sectors with the building industry, that is, environmental assessment methods encourage greater dialogue and teamwork. Although the developers of assessment tools continue to refine their scope, structure, and metrics, key issues are the interpretation placed on the final environmental profile or label by the "market," its significance alongside other design requirements, and the changing relationship between voluntary and regulatory mechanisms to improve building environmental performance. Moreover, while the term "sustainable" building is increasingly used and social and economic criteria are being added to the assessments, few current assessment methods have been designed and structured from the outset to embrace these considerations.

Introduction

Until the release of the *Building Research Establishment Environmental Assessment Method* (BREEAM) in 1990

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[1] little, if any, attempt had been made to establish an objective and comprehensive means of simultaneously assessing a broad range of environmental considerations. Building environmental rating methods offer a means to demonstrate that a building has been successful at meeting an expected level of performance in a number of declared criteria. They provide building owners with a credible and objective means to communicate to prospective tenants the environmental qualities of the building they are leasing and, by emphasizing more demanding performance goals and the benefits over typical practice, they offer the potential for reframing expectations.

Building environmental assessment methods typically consist of three major components:

- A declared set of environmental performance criteria organized in a logical fashion – the *structure*
- The assignment of a number of possible points or credits for each performance issue that can be earned by meeting a given level of performance – the *scoring*
- A means of showing the overall score of the environmental performance of a building or facility – the *output*

Deriving a final aggregate "score" invariably requires some form of "weighting" – either implicitly or explicitly – being applied to the constituent criteria to reflect their relative significance within the overall measure of performance. This weighting process, which can profoundly influence the final overall building performance designation, has consistently represented a key part of discussions on building environmental performance. Key issues here relate to need to establish a more rational basis for the derivation of weightings, how these reflect regional priorities, and whether they should be implicit or explicit in the scoring process.

The development of assessment methods has, for the main part, been driven by the scoping and structuring of performance criteria. Although it is generally accepted that environmental criteria must be organized in ways that facilitate meaningful dialogue and application, the structuring of criteria within the assessment method is most important during the *output* of the performance evaluation, when the "story" of the performance must be told in a coherent and informative way to a variety of different recipients. Gann et al. [2] indicate that the "methods by which results are depicted has a direct bearing on how the indicators are used and understood – and by whom." The Japanese *Comprehensive Assessment System for Building Environmental Efficiency* (CASBEE) [3], for example, explicitly distinguishes between the way that performance information is organized during the assessment process and how it is transformed to communicate a variety of different outputs. It uses a variety of different output formats, providing the opportunity to tell different "stories" about a building's performance – an overall performance as well as more detailed descriptions. Moreover, CASBEE, while employing an additive/weighting approach, breaks away from the simple addition of points achieved in *all* performance areas to derive an *overall* building score, which has been the dominant feature of all previous methods. It distinguishes between the *Environmental Loading* (resource use and ecological impacts) and *Environmental Quality and Performance* (indoor environmental quality and amenities), scoring them separately to determine the Building Environmental Efficiency, that is, the ratio of *Environmental Quality and Performance* to *Environmental Loading*. As such, the structure of the CASBEE itself conveys an eco-efficiency view of assessment.

Given that assessment methods function as voluntary, market place mechanisms, ensuring that the methods are simple, practical, and inexpensive in both use and maintenance is deemed paramount. This simple characterization of building environmental issues has both positive and negative impacts on building design. For owners and design teams beginning to address environmental issues, the simplicity provides a straightforward means of discovering what is important and what is not important. As such assessment methods can be an instrument for changing design practice by identifying a new standard of performance that encourages architects and engineers to break old habits and design norms. However, building environmental methods may, indirectly, detract from a more fundamental professional commitment to environmental responsibility. Currently, design teams and owners use assessment methods to collectively establish an overall desired "score" – a BREEAM "Excellent" or "Very Good," or a US Leadership in Energy and Environmental Design (LEED®) [4] "Gold" or "Silver" rating – and then review the range of individual performance criteria to identify those seen as being attainable. There is concern that "checklist" type environmental assessment methods may drive the product and process where simply achieving a high score, with many important gains, may prove more important than aspiring to the best overall product.

Environmental Assessment Methods

Assessment implies measuring how well or poorly a building is performing, or is likely to perform, against a declared set of criteria. Most current building assessment methods attempt to measure improvements in the environmental performance of buildings relative to current typical practice or requirements and have the following general characteristics:

- Are technically framed and emphasize the assessment of resource use, ecological loadings, and health and comfort in individual buildings
- Are primarily concerned with mitigation – reducing stresses on natural systems by improving the environmental performance of buildings
- Assess performance relative to explicitly declared or implicit benchmarks and, as such, measure the extent of improvement rather than proximity to a defined, desired goal
- Assess design intentions and potential as determined through prediction rather than actual real-world performance
- Structure performance scoring as a simple additive process and use explicitly declared or implicit weightings to denote priority
- Offer a performance summary, certificate, or label that can be part of leasing documents and promotional documents

Building environmental assessment is now a distinct and important realm of research and inquiry that seeks to develop greater refinement and rigor in performance indicators, weighting protocols, and, where appropriate, the potential incorporation of Life Cycle Assessment (LCA) approaches to refine the constituent measures. Moreover, it has provided numerous side-by-side comparisons of the more notable methods and tools (e.g., BREEAM, LEED®, CASBEE, and the Australian Green Star) to illustrate areas of convergence and distinction, typically as a starting point for generating applicable methods in other regions or countries seeking to develop new assessment schemes. Within this debate, the scope of comparison and analysis is typically based only on technical content (e.g., the framework) and makes little or no reference to the organizational or market context within which the methods operate; that is, comparisons are made indiscriminately between tools and methods. This represents a serious problem since the context within which an assessment method has been designed to operate profoundly affects the effective scope, emphasis, and rigor of an assessment.

Although initially introduced to perform a specific assessment role as a means to counter-act unverified claims of building performance – "green-wash" – building environmental assessment methods play a qualitatively different role in today's context. There are several emerging issues that increasingly frame the use of building assessment methods:

- Assessment methods have moved beyond voluntary market place mechanisms. Performance thresholds in the assessment methods (e.g., LEED® Gold) are increasingly being specified by public agencies and other organizations as performance requirements, and are being considered as potential incentives for development approval, bonus density, and other concessions.
- Building environmental assessment is increasingly being recognized by banking, financial, and insurance companies as a basis for risk and mortgage appraisals and real estate valuations.
- With more widespread adoption of assessment tools, compliance with performance requirements increasingly affects associated manufacturing industries. While some industries use this as an opportunity to reevaluate production processes, some become increasingly resistive.
- The range of building types seeking certification is increasing and this, in turn, is creating the need either to develop generic systems that can recognize

distinctions on an as-needed basis for specific situations or to create a suite of related methods and tools, each of which uniquely addresses a particular building type.

- The need to permit easy access to tools and methods, and to enable assessments to be made quickly and cheaply, is spurring the increased deployment of Web-based methods and electronic submission processes to attain certification.
- The aggregate effect of individual buildings has enormous consequence for community infrastructure design and operation. This, together with the inherent limitation of analyzing individual buildings as the basis to understand ecological impacts, has generated interest in creating and linking assessment methods and tools across a variety of scales.
- Increased awareness of the inevitability of climate change has extended the approach from solely one of mitigation to now embrace adaptation to changing conditions and the conscious restoration of previously degraded natural systems.

Proliferation of Building Environmental Assessment Methods

The field of building environmental assessment has matured remarkably quickly since the introduction of BREEAM, and the interim period has witnessed a rapid increase in the number of methods either in use or being developed worldwide. Within this relatively short time period, successive generations of systems have evolved as a result of accumulated experience, new conceptual insights, and theoretical propositions. Different systems have greater strengths and weaknesses than others, and later systems draw on these to include features and elements that permit more effective use. The past decade has witnessed a proliferation of building environmental assessment methods by countries worldwide for application within their respective domestic markets (see Table 1). Many of these systems have made considerable conceptual advances over early, more established methods. To date, however, with the exception of three or four systems, the number of assessed buildings in many countries using the domestic systems remains modest. This lack of traction is primarily due to the lack of the organizational and financial resources required to support the necessary educational, management, and certification programs.

There is little doubt that building environmental assessment methods have contributed enormously to furthering the promotion of higher environmental expectations and are directly and indirectly influencing the performance of buildings. Assessment methods have enjoyed considerable success and their widespread awareness has created the critical mass of interest necessary to cement their role in creating positive change. "Success" is used here in reference to the way that assessment methods have entered the parlance of the building industry rather than the number of actual "assessed" and "certified" projects – which is still relatively low compared to the total number of buildings constructed annually [5].

A number of factors have collectively generated the early momentum of assessment methods:

- The prior absence of any means to both discuss and evaluate building performance in a comprehensive way left open a distinct niche within an emerging European and North American "culture of performance assessment."
- The simple, seemingly straightforward declaration of the requirements of a discrete number of performance measures presented a complex set of issues in a manageable form.
- By offering a recognizable structure for environmental issues, they provided a focus for the debate on building environmental performance.
- Public sector building agencies have used them as a means of demonstrating commitment to emerging environmental policies and directives.
- Manufacturers of "green" building materials and products have been given the opportunity to make direct and indirect associations with the relevant performance criteria, to support the sales of "high" performance products. The range of environmental goals has led to the engagement of diverse professional expertise early in the design process with collaborative decision-making processes emerging.

Because of this momentum, building environmental assessment methods have dwarfed all other mechanisms for instilling environmental awareness within the building industry. Indeed, over the past decade they

Rating Systems for Sustainability. Table 1 Building environmental assessment methods and tools in use worldwide

Region	Country	Name	Owner/Management
Europe	France	HQE Method	HQE (*Haute Qualité Environnementale)*
	Finland	PromisE	VTT (Technical Research Centre of Finland)
	Germany	Sustainable Building Certificate	German Sustainable Building Council
	Italy	Protocollo ITACA	iiSBE Italia
	Norway	Envir. Programming of Urban Development	SINTEF (Skandinavias største uavhengige forskningsorganisasjon)
	Portugal	LiderA (Leadership for the Environment in Sustainable Building)	Instituto Superior Técnico, Lisbon
	Spain	VERDE	Spanish GBC
	Sweden	EcoEffect	Royal Institute of Technology
	Netherlands	BREEAM-NL	Dutch GBC
	UK	BREEAM (Building Research Establishment Environmental Assessment Method)	Building Research Establishment
	Europe	LEnSE (Label for Environmental, Social & Economic building)	Belgian Building Research Institute
N. America	United States	LEED® (Leadership in Energy and Environmental Design)	United States GBC
		GreenGlobes	Green Building Initiative
	Canada	LEED-Canada	Canada GBC
		GreenGlobes	ECD Canada
	Mexico	SICES	Mexico GBC
Asia	China	GHEM (Green Housing Evaluation Manual)	Ministry of Construction
		GOBAS (Green Olympic Building Assessment Scheme)	Ministry of Science & Technology
		ESGB (Evaluation Standards of Green Building)	Ministry of Housing and Urban-Rural Construction
	Hong Kong	BEAMPlus	HK-BEAM Society
		CEPAS (Comprehensive Environmental Performance Assessment Scheme)	HK Building Department
	India	TERI-GRIHA (Green Rating for Integrated Habitat Assessment)	TERI (The Energy & Research Institute)
		LEED-India	Indian GBC
	Japan	CASBEE (Comprehensive Assessment System for Building Environmental Efficiency)	Japan Sustainable Building Consort.
	Korea	GBCC (Green Building Certification Criteria)	Korean Korea Institute of Energy Research

Rating Systems for Sustainability. Table 1 (Continued)

Region	Country	Name	Owner/Management
	Singapore	Green Mark	Singapore Building & Construction Authority (BCA)
	Taiwan	EEWH (Ecology, Energy, Waste and Healthy)	ABRI (Architecture and Building Research Institute)
	Vietnam	LOTUS	Vietnam GBC
Southern H.	Australia	Green Star	Australian GBC
		NABERS (National Australian Building Environmental Rating Scheme)	
	Brazil	LEED-BRAZIL	GBC Brazil
		HQE	Fundação Vanzolini
	New Zealand	Green Star NZ	New Zealand GBC
	S. Africa	Green Star SA	South African GBC
		SBAT (Sustainable Building Assessment Tool)	CSIR (Council for Scientific and Industrial Research)
Generic		GBTool/SBTool	iiSBE (International Initiative for a Sustainable Built Environment)
		SPeAR (Sustainable Project Assessment Routine)	Ove Arup Ltd.

GBC – Green Building Council

have been positioned as the most potent mechanism for affecting change.

Sustainability Assessment

The majority of current building environmental methods assess *environmental* performance improvements *relative* to typical practice, either implicitly or explicitly. They are also set within the parlance of marketing practice, and the intentions for such systems and the individual assessment credits that comprise them are understandable by all the stakeholders. Since its introduction in 1987, "sustainability" has emerged as a widely held and necessary overarching notion to frame and guide all future human activity and enterprise. An emerging debate on building assessment relates to shift from environmental or "green" performance to this larger goal of sustainability.

The need to develop methods of deliberation and decision making that actively engage the relevant interests of stakeholders will become increasingly important to infuse sustainability considerations into day-to-day conduct and practice. Robinson [6] suggests that the "power of sustainability lies precisely in the degree to which it brings to the surface these contradictions and provides a kind of discursive playing field in which they can be debated" and subsequently encourage the "development of new modes of public consultation and involvement intending multiple views to be expressed and debated." Again, the parallel debate in building environmental assessment is becoming increasingly evident. Kaatz, Root, and Bowen [7], for example, advocate the implementation of a broader participatory approach in building assessment, including consideration of process design, definition of desired outputs and outcomes, etc.

Sustainability relates to a suite of concepts and embraces notions other than environmental performance, and as such is open to wider interpretation. However, it has two implicit requirements. Firstly, within the constituent dimensions of sustainability – environmental, social, and economic – is a responsibility to inter- and intra-generational equity. Secondly, sustainability, and any discussion of it, requires thinking long-term and assuming responsibility to the future. However, the ideal of the principles of sustainability is one thing, their assimilation and practice within the building industry is somewhat different. Whereas it is possible to define "green" and even "greener" as well as the incremental process for improving performance, it is currently difficult to envision and articulate a sustainable future – either in general terms or as related to the configuration of human settlement. It is therefore difficult to have confidence in the design of effective assessment systems when it is not possible to link them to final results. Moreover, short-sighted economic priorities and gains have always compromised environmental and social considerations in building.

Although the building development industry is fundamentally risk averse, this tendency is not evident in either recognizing or responding to larger environmental issues. Despite powerful arguments on the importance of environmental issues and evidence on the multiple benefits of early adoption of higher performance standards, the construction industry procrastinates in making changes that are perceived to increase initial cost. While the fundamental idea of economic sustainability relates to long-term and shared economic benefit, the short-term mind-set of the building industry is using the language of sustainability to maintain the status quo. What is increasingly evident at the level of the individual building is the notion of "economic sustainability" being appropriated as simply dealing with the costs of building production, and thereby relegating environmental performance issues to being included only if they make economic sense.

Sustainability Assessment Methods

The Living Building Challenge (LBC) [8], launched in August 2006, is emerging in North America as a recognized and complementary performance aspiration to LEED®. Rather than permitting choice of credits to attain an overall performance score, the LBC requires 20 demanding performance requirements – including net-zero energy – to be met before the designation of Living Building is granted. However, while it references natural systems and uses a flower/petals metaphor, there is no recognizable organization of the issues based on ecological or systems theory. Similar to LEED® and the majority of other current assessment methods, the structure is simply a list of required performance requirements set within a defined set of categories.

A number of assessment tools have been introduced that expand on the range of performance issues to explicitly include social and economic criteria and thereby attempt to provide a measure of "sustainable" performance:

- *Ove Arup's Sustainable Project Assessment Routine SPeAR®* [9]: Functions as a project assessment methodology within Ove Arup's consulting projects to enable a rapid review of the sustainability of projects, plans, products, and organizations. Performance criteria are organized in four general sustainability categories: *Environment* (Air Quality, Land Use, Water, Ecology and Cultural Heritage, Design and Operation, and Transport); *Natural Resources* (Materials, Water, Energy, Land Utilization, and Waste Hierarchy); *Economic* (Social Benefits and Costs, Transport, Employment/Skills, Competition Effects, and Viability); and *Societal* (Health and Welfare, User Comfort/Satisfaction, Form and Space, Access, Amenity, and Inclusion). The SPeAR® diagram combines, in a graphical format, the diverse issues that need to be considered in sustainable design, including social, economic, natural resource, and environmental issues, acknowledging both negative and positive results. SPeAR® can be used to highlight areas where a project/design/development performs poorly in terms of sustainability principles, and to identify opportunities to optimize performance, integrate best practice, or utilize new technology. SPeAR® provides a basis for evaluating a project's sustainability performance not in comparison with that of other buildings, but relative to strengths and weaknesses within a particular context. This permits a greater level of subjectivity in the definition of performance criteria and their interpretation during scoring.
- *iiSBE's Sustainable Building Tool (SBTool)* [10]: The current version of *SBTool* is arranged in seven Performance Issues: Site Selection, Planning, and Development; Energy and Resource Consumption;

Environmental Loadings; Indoor Environmental Quality; Service Quality; Social and Economics Aspects; and Cultural and Perceptual Aspects. Whereas previous versions had focused on three distinct building types – Office buildings, Multi-Unit Residentials, and Schools – the current version allows a more generic description of buildings with multiple occupancies.

- *South African Sustainable Building Assessment Tool (SBAT)* [11]: Since the social and economic concerns in developing countries are far more pressing than those in developed countries, domestic constraints on environmental progress are therefore qualitatively different. SBAT explicitly introduces performance criteria that acknowledge social and economic issues [12]. A total of 15 performance areas are identified, equally divided within the overarching sustainability framework of environmental, social, and economic categories, each described through 5 performance criteria. Further, SBAT considers how it could become an integral part of, and subsequently influence, the building production process by relating its application to a nine-stage process based on the typical life cycle of a building: Briefing, Site Analysis, Target Setting, Design, Design Development, Construction, Handover, Operation, and Reuse/Refurbish/Recycle.
- *German Sustainable Building Council's Certificate Program* [13]: Five general sustainability "quality" categories are assessed and they form the overall aggregate building score: Ecological; Economic; Socio-cultural and Functional; Technical; and Process. A sixth quality with six sub-criteria – location – is evaluated and presented separately. Criteria within these performance areas are evaluated individually and aggregated to determine an overall performance designation of gold, silver, or bronze.

Robinson [6] suggests that if sustainability is to mean anything, "it must act as an integrating concept" and will require "new concepts and tools that are integrative and synthetic, not disciplinary and analytic; and that actively creates synergy, not just summation." When judged against these criteria, most current assessment methods and tools are left wanting in their ability to provide either insights or effective guidance on sustainability. A sustainable building is likely to be judged by the way that various systems fulfill multiple functions and, indeed, it is typically only possible to achieve high environmental performance within demanding cost and time constraints through the creative integration of systems. Similarly, while the three domains of environmental, social, and economic are typically used to frame sustainability, it is their points of intersection that are equally critical, that is, the ways and extent to which they positively or negatively influence each other. Simply adding social criteria to the current mix of environmental performance measures may not necessarily expose the way that one influences and is influenced by others. It can only do so if the method or tool is used as part of the deliberations between various stakeholders, that is, synergies are achieved through active, cross-disciplinary use of the tool, rather than simply the structure of the tool itself. That stated, it is important to ensure that environmental and social goals are not, yet again, compromised within this process.

Cross-Scale Assessment At a more pragmatic level, the notion of assessing the sustainability of an "individual" building is clearly problematic. Although one can assess the relative extent to which measures have been taken in an individual building to reduce resource use and ecological loadings, it is not possible to identify their effectiveness at addressing or furthering economic and social progress by relating them to regional or national indicators. Indeed, Gibberd suggests that "there is no such thing as a sustainable building – only buildings that enable people to live and work in sustainable ways" [14]. Assessing the ways and extent that buildings contribute progress toward sustainability will require understanding linkages across a range of scales.

Existing environmental assessment methods were primarily conceived to assess *individual* buildings, and performance issues are bounded by those factors that influence and are influenced by them. Many of the major building environmental assessment methods offer a suite of products each targeted at a specific building type or situation. The sequence in the development of assessment methods is important in revealing the increasing acknowledgment of a broader context. The majority began with a version for new office buildings and then subsequently expanded the range of products to include existing office buildings, multi-unit residentials, and then other broader applications – schools, homes, etc. Several existing systems have recently introduced versions that address a broader context, for example, USGBC's *LEED for Neighbourhood Development (LEED-ND®)*, *CASBEE for Urban Development (CASBEE-UD)* and *BREEAM Communities*. The fact that these were developed *after* gaining experience with assessing individual buildings is remarkably telling – development has been from the scale of individual buildings upward to that of a neighborhood scale rather than setting building performance within the overarching context of a neighborhood, community, or city.

Future Directions

There are several emerging trends that will shape the future design, roles, and use of assessment tools.

Voluntary and Regulatory Mechanisms

Given the pressing time-scale of anticipated significant climate change, it is difficult to imagine that a sustainable system of production and consumption will emerge from simply tweaking current practice. A key issue, therefore, lies in the considerable difference between the levels of change that the scientific community is advocating and those that are socially and politically acceptable. Similar arguments relate to the difficulties of making significant leaps forward in achieving widespread sustainable building practices within the acknowledged conservative and cost-sensitive context of the building industry. The majority of current "green" environmental assessment methods are voluntary in their application and have the primary objective of stimulating market demand for buildings with improved environmental performance. Indeed, the "acceptance" of current assessment methods currently derives largely from their voluntary application. However, the voluntary nature of existing methods significantly compromises both their comprehensiveness and rigor. Voluntary building environmental assessment methods must serve two conflicting requirements – they must function as an objective and sufficiently demanding metric to have credibility within the environmental community, while simultaneously being attractive to building owners who wish to have something positive to show for *any* effort that they have placed on environmental performance. Satisfying these twin requirements invariably compromises both the number of criteria that are assessed, where the benchmarks are set before performance points are earned and what is presented as the most demanding performance target.

Higher environmental performance requirements are increasingly being mandated bringing into question the ways that voluntary assessment methods will have to be cast within a broader array of mechanisms for creating necessary change. Here, the current success that assessment methods enjoy within both research and practice has potentially adverse consequences. By being almost the sole focus of the debate, too much expectation may be being placed on their ability to create the necessary change.

Given the practical (and incentive) constraints on setting demand targets and dependency on market acceptance, it is uncertain whether voluntary mechanisms will ultimately be sufficient to create the necessary improvements in environmental performance of buildings needed to meet broader national environmental or sustainability targets. As such, the relationship between building environmental assessment methods and other change instruments, both regulatory and incentive based, will gain in importance [15]. Historically, regulation provided minimal acceptable performance requirements, and the voluntary mechanisms offer the complementary high performance aspiration. Recently, the mandates of far reaching performance requirements such as carbon neutrality will profoundly change these roles. In Europe, for example, demanding energy and carbon emission standards for buildings are now being introduced requiring phased reductions to net-zero energy performance [16, 17]. In North America, the recent development of ASHRAE 189.1-2009 [18] jointly by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), the Illuminating Engineers Society (IES), and the US Green Building Council (USGBC) sets green building performance criteria within a regulatory framework.

Achieved Performance

The assessment of building environmental performance of new buildings is typically made at the design stage and based on default patterns of occupant behavior and building operation. There is sufficient evidence to show that a building's performance in use is often markedly different from that anticipated or predicted during design and this discrepancy has initiated a shift toward basing assessments on achieved performance.

The owners and developers of any of the major assessment systems are actively seeking data on the actual performance of buildings, particularly energy and water use, and energy-related emissions. The Canada Green Building Council (CaGBC), for example, adopted the 2030 Challenge which aims for net-zero buildings by 2030 [19] and has set targets of 50% measured reductions in energy and water use from a 2005 baseline for 100,000 buildings and 1,000,000 homes by 2015. These targets cover existing and new building stock, and represent 20% of all buildings in Canada, two-thirds of total building space, and 10% of all Canadian homes. To meet these targets, the CaGBC introduced the Green Building Performance Initiative in 2008 that involves performance benchmarking, auditing, action planning and verification have informed the development and testing. GREEN UP – Canada's Building Performance Program – is providing online tools, standards, and continuously updated performance information to building owners and managers across Canada [20]. The current program is addressing performance in energy and water use, and energy-related emissions, using monthly utility billing as the data source.

Building Valuation

The need to establish a business case for the development of "green" or/and sustainable commercial properties within the real estate industry has paralleled the technical development and application of building environmental assessment methods [21]. Although the possible capital cost premiums associated with attaining higher building environmental performance has been a recurring issue over the past 20 years, the emphasis of these economic considerations has changed considerably. Initially, the business case was framed around the added benefit and reduced revenue costs to the building owner. Today, however, the business case is increasingly rooted in the added value associated with higher building environmental performance and the demonstration that green buildings may be "worth more" to investors, owners, and tenants [22].

Whereas the cost arguments have consistently referenced building environmental assessments, for example, the cost of LEED [23, 24], very little attention has been directed at connecting green rating to value. CASBEE is the first system to introduce a version explicitly linking building environmental performance assessment with real estate appraisal. CASBEE for Property Appraisal [25] is an "appraisal support tool that measures the impact degree of [design for the environment] on the property value" that when widely applied will significantly increase the demand for green buildings.

Regionalization and Standardization

The past decade or so has witnessed many countries worldwide now either having or in the process of developing domestic systems. This carries the implicit expectation for domestic systems to encourage green building practices appropriate to their specific climatic and cultural contexts. Moreover, many of these systems include innovative conceptual advances over the earlier more established methods. With the exception of iiSBE's *SBTool* and the more recent *LEnSE* project [26] that have generic core frameworks and criteria but were designed from the outset to permit regional customization, the majority of recognized assessment methods are country or context specific. All assessment tools carry the values and priorities of their authors, either implicitly or explicitly, raising questions regarding the ways and extent that – without significant adaptation – they can be meaningfully adopted by other countries. Moreover, the organizational context in which assessment methods reside, that is, who owns and manages them, is critical in terms of the credibility of the method for the broad range of industry and client stakeholders, and the human and financial resources available to maintain and implement the method. These attributes are equally significant in the marketing and widespread use of systems internationally.

Similar to the necessity and value of developing standardized Life Cycle Assessment protocols for building materials and products, that is, universal criteria for establishing boundary conditions, data quality, etc., there is increased activity in defining standardized requirements for building assessment methods (e.g., ISO TG59/SC17: Sustainability in Building Construction) [27].

Given the proliferation of domestic assessment systems worldwide over the past 15 years, a number of developments are now pushing toward increased standardization. A primary driver for this development is organizations seeking a common international vocabulary for building environmental assessment that can then facilitate communication between stakeholders and inter-building and inter-country comparisons [28]. A recent development in Europe has been the establishment of the *Sustainable Building Alliance* (SBA) [28] and the *International Sustainability Alliance* (ISA) [29]. The French *Centre Scientifique et Technique du Bâtiment* (CSTB), UK *Building Research Establishment* (BRE), and others launched the *Sustainable Building Alliance* (SBA) in April 2008 with the aim of establishing common metrics for key issues so as to provide transparency between rating systems while, importantly, still recognizing regional and national differences.

The BRE initiated the International Sustainability Alliance (ISA) in late 2009 to "drive the development of common international standards for real estate" by providing an international governance structure that "join forces with international companies, Green Building Councils, research institutes and other stakeholders in the real estate chain toward an international sustainability standard for the built environment" [30]. ISA stated goals include:

- Driving toward one single European certification standard, adaptable to local market conditions
- Expanding on the current BREEAM system and creating a third Generation System for the market and industry

Methods are owned and operated by a wide range of private and public sector organizations. However, one of the most significant developments regarding the organizational context for building environmental assessment methods is the increase in the number of *Green Building Councils* [31], their linkage through the *World Green Building Council (WorldGBC)* [32], and their sharing experiences with using assessment methods. Two aspirations with the World GBC's mission are to ensure Green Building Councils are successful and have the tools necessary to advance and to support effective green building rating systems. The ways and extent to which the various member Councils favor certain assessment tools remain uncertain at this time.

Branding

An often-stated role and expectation is that the widespread adoption of assessment methods could ultimately transform the market in its expectation and demand for buildings with higher environmental performance. Almost all current building environmental assessment methods are voluntary in their application and have the primary objective of stimulating market demand for buildings with improved environmental performance. This has been accompanied by the notion of "branding" the names of LEED® and BREEAM to building owners, purchasers, and lessors to make them synonymous with high levels of environmental performance and companion mechanisms such as the LEED Accredited Professional program to "transform" expectations and valuation of skills and knowledge of design professionals. While "branding" the assessment methods domestically is obviously a necessary process for their promotion and adoption, there is also a clear shift to the support for a few international "brand-name" systems. The primary drivers here include:

- Multinational companies who have building/development projects worldwide and who are expected to adhere to numerous national environmental assessment methods
- Corporations/companies that need to acquire green buildings when they are operating internationally to fulfill their corporate sustainability requirements
- Manufacturers of green building products who are expected to adhere to numerous national environmental assessment methods

BREEAM and LEED® are two of the oldest and most widely internationally recognized systems and, by virtue of this, have the greatest presence outside their countries of origin. They are also being increasingly positioned as being in competition within a global market [33, 34].

BREEAM Abroad Early in its development, there was a declared aspiration that BREEAM would have an international presence. In 1997, Doggart and Baldwin reported that "BREEAM type schemes have now been developed in other countries and regions, such as Hong Kong and Canada" and that "BREEAM versions are also being developed in Denmark, Norway, Australia, New Zealand and USA" [35]. While this did not materialize, the need for some level of regional adaptation was also explicitly referenced.

BRE Global now presents BREEAM as "the world's leading environmental assessment method for buildings and now communities" [36] with over 110,000 buildings certified and over half a million registered for certification [37]. BREEAM is currently having influence internationally in terms of using *BREEAM Bespoke International* or country-specific versions. Versions of BREEAM have been created for Europe and the Gulf, a country-specific version for the Netherlands, and Memorandum of Understanding has been signed between BRE Global and a group in Spain and with the Russian and Turkish GBCs, for the introduction into those respective countries.

LEED Abroad LEED® is having influence beyond the USA in terms of various countries adapting the system for their own markets or through overseas owners having buildings assessed through the USGBC:

- The Canadian and Indian Green Building Councils have created adaptations of LEED®, while groups in Brazil, Argentina, Italy, and a dozen other countries are developing/using adaptations of LEED® [38].
- The recent creation of the Green Building Certification Institute (GBCI) – established with the support of the USGBC – allows for "balanced, objective management of the LEED Professional Accreditation program, including exam development, registration, and delivery." As of January 2010, the GBCI's website records that LEED Accredited Professions are currently in 84 countries worldwide, the largest being: USA, 126,750; Canada, 1,314; China (including Hong Kong), 936; UAE, 622; UK, 280; India, 267; South Korea, 212; Mexico, 106 [39].

While the picture is not entirely clear regarding the extent of use of the BREEAM and LEED® internationally, with registered/certified projects in 103 countries the LEED® "brand" appears to currently have the greater uptake globally. Domestic and international property developers appear to be becoming increasingly interested in certifying their buildings to LEED® in order to attract these companies to move in. It is anticipated that as more and more companies move into the China market, the demand for LEED® certified buildings will further increase.

Building environmental assessment and labeling programs are considered one of the most potent and effective means to both improve the performance of buildings and transform market expectations and demand. Indeed, the environmental performance assessment of buildings is now a major business, with significant revenues generated through the certification process, licensing of the systems, training and education, and the accrediting of professionals. Many countries around the world clearly have domestic methods that will remain the sole or dominant system within their respective markets, for example, Green Star in Australia and New Zealand, CASBEE in Japan, and Green Mark in Singapore. However, there are many other countries and regions where BREEAM, LEED®, and other systems will expand their presence over the next decade as a result of increased demand and active promotion. Market forces and "branding" will, in the fullness of time, invariably play a role in dictating the extent to which voluntary systems become de facto international approaches. While there are numerous benefits for consistency in how certain performance measures are defined and evaluated, such as energy and carbon emissions, the ways and extent that methods both recognize and accommodate cultural and contextual differences when deployed internationally will remain decisive in shaping a positive outcome.

Given the increased deployment of the major systems internationally and the significance of global building practices, it is also highly likely that there will be some level of harmonization between the major tools to enable international benchmarking, especially in relation to greenhouse gas emissions, that is, the introduction of a commonly recognized standard/metric for measuring and recording energy use and carbon emissions, which could be adopted by multiple tools.

The benefits of assessment methods have been considerable: providing more comprehensive performance goals for buildings, supporting collaborative design processes, changes in economic investment, changes in industry, international collaboration, etc. They will continue to evolve in response to a host of current challenges such as ensuring that delivered performance matches design intentions, accommodating community and regional goals and priorities, and supporting a more comprehensive integration of human and natural systems.

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Regenerative Development and Design

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Article Outline

Glossary

Biomimicry Sometimes called biomimetic design, an emerging design discipline that looks to nature for sustainable design solutions [1].

Cradle to Cradle® Framework for designing manufacturing processes "powered by renewable energy, in which materials flow in safe, regenerative, closed-loop cycles," and which "identifies three key design principles in the intelligence of natural systems, which can inform human design: *Waste Equals Food*; *Use Current Solar Income*; *Celebrate Diversity*" [2, 3].

Ecoliteracy The ability to understand the natural systems that make life on earth possible, including understanding the principles of organization of ecological communities (i.e., ecosystems) and using those principles for creating sustainable human communities [4, 5].

Ecological sustainability A biocentric school of sustainability thinking that, based on ecology and living systems principles, focuses on "the capacity of ecosystems to maintain their essential functions and processes, and retain their biodiversity in full measure over the long term"; contrasts with technological sustainability based on technical and engineering approaches to sustainability [4].

Ecology The interdisciplinary scientific study of the living conditions of organisms in interaction with each other and with the surroundings, organic, as well as inorganic.

Ecosystem "The interactive system of living things and their nonliving habitat" [6].

Ecosystem concept "A coherent framework for redesigning our landscapes, buildings, cities, and systems of energy, water, food, manufacturing, and waste" through "the effective adaptation to and integration with nature's processes." It has been used more to shape an approach than as a scientific theory [7].

Living systems thinking A thinking technology, using systemic frameworks and developmental processes, for consciously improving the capacity to apply systems thinking to the evolution of human or social living systems [8].

Locational patterns The patterns that depict the distinctive character and potential of a place and provide a dynamic mapping for designing human structures and systems that align with the living systems of a place.

Pattern literacy Being able to read, understand, and generate ("write") appropriate patterns.

Permaculture A contraction of *permanent agriculture* or *permanent culture*, permaculture was developed as a system for designing ecological human habitats and food production systems based on the relationships and processes found in natural ecological communities and the relationships and adaptations of indigenous peoples to their ecosystems [9].

Place The unique, multilayered network of ecosystems within a geographic region that results from the complex interactions through time of the natural ecology (climate, mineral, and other deposits, soil, vegetation, water, and wildlife, etc.) and culture (distinctive customs, expressions of values, economic activities, forms of association, ideas for education, traditions, etc.).

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Regenerate American Heritage Dictionary of the English Language and Merriam Webster Dictionary
- To give new life or energy; to revitalize; to bring or come into renewed existence; to impart new and more vigorous life
- To form, construct, or create anew, especially in an improved state; to restore to a better, higher or more worthy state; refreshed or renewed
- To reform spiritually or morally; to improve moral condition; to invest with a new and higher spiritual nature
- To improve a place or system, especially by making it more active or successful

Regenerative design A system of technologies and strategies based on an understanding of the inner working of ecosystems that generates designs to regenerate rather than deplete underlying life support systems and resources within socioecological wholes.

Regenerative development A system of technologies and strategies for generating the patterned whole-system understanding of a place, and developing the strategic systemic thinking capacities and the self-organizing and self-evolving stakeholder engagement/commitment required to ensure regenerative design processes achieve maximum systemic leverage and support.

Restorative design Sometimes called restorative environmental design, a design system that combines returning "polluted, degraded or damaged sites back to a state of acceptable health through human intervention" [10] with biophiliac designs that reconnect people to nature.

Source to sink Simple linear flows from resource sources (farms, mines, forests, watershed, oilfields, etc.) to sinks (air, water, land) that deplete global sources and overload/pollute global sinks [11].

Systems thinking A framework for seeing interrelationships rather than things and for seeing patterns of change rather than static "snapshots." It addresses phenomena in terms of wholeness rather than in terms of parts [5].

Definition of the Subject and Its Importance

The emerging field of regenerative development and design marks a significant evolution in the concept and application of sustainability. Practices in sustainable or green design have focused primarily on minimizing damage to the environment and human health, and using resources more efficiently, in effect, slowing down the degradation of earth's natural systems. Advocates of a regenerative approach to the built environment believe that a much more deeply integrated, whole-systems approach to the design and construction of buildings and human settlements (and nearly all other human activities) is needed. Regenerative approaches seek not only to reverse the degeneration of the earth's natural systems but also to design human systems that can coevolve with natural systems – evolve in a way that generates mutual benefits and greater overall expression of life and resilience. The field of regenerative development and design, which draws inspiration from the self-healing and self-organizing capacities of natural living systems, is increasingly seen as a source for achieving this end. This field is redefining the way that proponents of sustainability are thinking about and designing for the built environment, and even the role of architecture as a field.

Introduction

Chronology

Early Roots In the 1880s, Ebenezer Howard wrote *To-morrow: A Peaceful Path to Social Reform*. Reissued in 1902 as *Garden Cities of To-Morrow*, with an introductory essay by Lewis Mumford, the book was an early and influential expression of ecological thinking applied to human settlement. It sought to reconnect humans to nature, and featured use of natural rather than engineered processes to build the health of the system. His description of a utopian city in which man lives harmoniously together with the rest of nature stimulated the founding of the garden city movement and the establishment of several Garden Cities in Great Britain in the early twentieth century [11, 12].

In 1915, Patrick Geddes published his study of the urban growth patterns stimulated by the mass movement of people into cities [13]. Geddes, a biologist, saw cities as living organisms. He believed that addressing the problems of unsustainable growth required understanding a city's context – the surrounding landscape's natural features, processes, and resources – and called for a solid analytic method for developing that understanding. His conclusion would influence regional planning movements across Europe and the United States. Geddes applied the terms *Paleotechnic* and *Neotechnic* to distinguish the industrial era producing this destructive growth of human settlements from the era he predicted would follow its demise. These terms would be picked up by John Tillman Lyle, some 80 years later, to differentiate industrial era and regenerative technologies. Some trace the origins of ecological design to the work of Patrick Geddes [7, 11].

Development of the Ecosystem Concept and Ecological Perspective In 1935, Arthur Tansley introduced an entirely new concept to ecology in his work, "The Use and Abuse of Vegetational Concepts and Terms" [6]. He proposed the term *ecosystem* as a name for the interactive system of living things and their nonliving habitat and the application of systems science as a way to bring more scientific rigor to the study of nature's complexity and the effect of human activities on that complexity. Tansley and other organismic biologists of the period were the first to formulate a systems view of life. Seeking a more accurate depiction of how life ordered and organized itself within a particular landscape or geographic location, he posited that neither a living organism nor its physical environment could be thought of as separate entities: "we cannot separate them from their special environment, with which they form one physical system." Two of the most significant implications of this depiction of how life structures itself were the deconstruction of the human/nature dichotomy that had shaped Western design thinking and the establishment of the premise that all species are ecologically integrated with each other, as well as with the abiotic constituents of their biotope or habitat. For Tansley and other ecologists concerned about the increasing impact of humans on natural systems, the ecosystem offered a valuable framework for analyzing the effect of human activities on natural systems and resources. In later years, the concept was further defined or clarified to explicitly include a social complex (human social institutions and actions) and a built complex (structures and infrastructures) and became a framework for sustainable urban planning and development [14, 15].

In the 1950s and 1960s, Eugene and Howard Odum laid the foundation for the development of ecology into a modern science, based on the core concept of the ecosystem as the fundamental ordering structure of nature. They published the first textbook on ecology, *The Fundamentals of Ecology*, in 1953. Their work brought attention to the importance of understanding how the earth's ecological systems interact with one another. Howard Odum further developed a number of key theoretical concepts and methodologies including his "energy systems language," a set of symbols used to compose energy flow diagrams for any scale system [16]. His study of wetlands pioneered the now widespread approach of using wetlands as water quality improvement ecosystems and served as an important contribution to the beginnings of the field of ecological engineering [17].

New Foundations for Systems Theory and Systems Thinking In 1968, biologist and systems theoretician Ludwig von Bertalanffy published his *General System Theory: Foundations, Development, Applications*. General systems theory (GST) introduced the concept of open systems, emphasized the difference between physical and biological systems, and introduced evolutionary thinking – thinking focused on change, growth, and development [18]. GST opened the door to a new science of complexity. The recognition that complex systems cannot be understood through simple analysis led to the emergence of systems thinking as a major scientific field, a profound change from the analytic, reductionist mode that had dominated Western scientific thinking since the time of Descartes, Newton, Galisteo, and Bacon. GST also laid the basis for the development of living systems science, for Charles Krone's development of living systems thinking and their application to natural systems, as well as to human social systems. His work strongly influenced Howard Odum's ecosystem modeling and energetics, which, in turn, influenced John Tillman Lyle's work on regenerative design technologies.

In the 1960s–1970s – systems theorist and architect of organizational processes and structures, Charles Krone developed living systems thinking as a developmental technology for consciously improving systems thinking capacity. His work drew on and greatly extended GST and *Systematics*, a discipline developed by mathematician John Bennett that uses systemic frameworks to understand complex wholes within which people are participants rather than observers. The systemic frameworks and developmental processes Krone generated were applied and evolved within businesses. Their purpose was to create an understanding of businesses, communities, and nature as living systems and to build the consciousness required to create reciprocally beneficial relationships through better integration of industrial, community, and natural processes. His work served as a core foundation for Regenesis Collaborative Development Group as they developed and evolved regenerative development processes and technologies, starting in the 1990s [19, 20, 21]. Of particular importance for regenerative development was Krone's framework depicting four orders or levels of work that living systems of all scales need to carry out. Ranging over four levels from basic operations up through regenerative work, it allows practitioners to design for the integrated evolution of all levels of work in support of a regenerative change process.

Ecological Sustainability – Foundations of Regenerative Development and Design In 1969, Landscape architect Ian McHarg published *Design with Nature*, pioneering a technology for ecological land-use planning based on understanding natural systems [22]. His book became a foundational textbook for the ecological view of urban landscape design, and its basic concepts were later developed into the geographic information systems (GIS) – a critical tool for ecological development.

In 1978, Bill Mollison, an Australian ecologist, and one of his students David Holmgren coined the word permaculture from a contraction of *permanent agriculture* or *permanent culture*. They developed the field of permaculture as an ecological design system to promote design of human habitats and food production systems based on the relationships and processes found in natural ecological communities. Much of its inspiration was drawn from the relationships and adaptations of indigenous peoples to their ecosystems [9]. Like ecological practitioners such as Ian McHarg, Mollison and Holmgren espoused integration of human and natural environments, but they also developed design technologies and practices for increasingly self-sufficient human communities and food production systems. By creating "man-made ecosystems," permaculture demonstrated how to provide for a host of human needs while reducing dependence on environmentally destructive industrial practices. While earlier iterations of ecological design promoted integration of human and natural systems for more sustainable development, permaculture was the first ecological design system to introduce the concept of a regenerative effect as a new standard of ecological performance for the built environment – the generation of a surplus or overabundance of energy and resources that could be reinvested to evolve natural and human living systems as an integrated whole. In support of that goal, Mollison's *Permaculture: a designers' manual*, published in 1988, introduced a hierarchy of investment (regenerative, generative, and degenerative) as a framework for assessing the value of potential actions for building regenerative capacity in a system [9].

Also in the 1980s, Robert Rodale, son of organic agriculture pioneer J. I. Rodale, advanced the use of the word *regenerative* in relation to the use of land, calling for going "beyond sustainability, to renew and to regenerate our agricultural resources" [23]. Rodale used the term to describe the continuing organic renewal of the complex living system that he saw as the basis for healthy soil and, in turn, for healthy food and healthy people. He later applied the same principle of ongoing self-renewal to regenerative economic development [24]. While his work did not extend to the built environment, his principles influenced John Tillman Lyle's work and are foundational in the subsequent conceptualization and application of regenerative methodologies to all of the systems that support life.

In 1984, John Tillman Lyle published *Design of Human Ecosystems* [25] in which he argued that "designers must understand ecological order operating at a variety of scales and link this understanding to human values if we are to create durable, responsible, beneficial designs." He defined human ecosystems as "places in which human beings and nature might be brought together again" for mutual benefit and posited conscious ecosystemic design as essential to a sustainable future. The book introduced several key concepts that laid the basis for his subsequent work on regenerative design (below). These included (1) "shaping ecosystems, just like shaping buildings," requires a set of organizing principles drawn from "strong concepts of an underlying order that holds the diverse pieces and all their hidden relations together." (2) In ecosystem design, "these underlying concepts of order are drawn from ecology" and principles for ecosystem design draw from the "need to comprehend and envision the ecosystem the designer is seeking to shape as a dynamic (living) whole," and (3) ecological concepts are "more or less analogous to the laws of mechanics in architecture in that they provide us with organizing principles for shaping ecosystems much as architects shape buildings."

Ecological Design Systems Proliferate The 1990s was a period of intense creative ferment for ecological design thinking. A number of foundational books were published laying out both the practical and theoretical bases of design for ecological sustainability, including *Ecological literacy: education and the transition to a postmodern world* by David Orr (1992), *From Eco-Cities to Living Machines: Principles of Ecological Design* by Nancy Jack Todd & John Todd (1993), *The web of life: A new scientific understanding of living systems* by Fritjoff Capra (1995), *Ecological Design* by Sim van der Ryn and Stuart Cowan (1996), and *The ecology of place: Planning for environment, economy, and community* by Timothy Beatley (1997).

In 1992, educator David Orr and physicist Fritjof Capra coined the term ecological literacy (also referred to as *ecoliteracy*) to describe the ability to understand the natural systems that make life on earth possible, including understanding the principles of organization of ecological communities (i.e., ecosystems) and using those principles for creating sustainable human communities [4].

Also in the 1990s, new ecological and living system-based metric systems were introduced, including the revision of architect Malcolm Wells' Wilderness-Based Check-list for Design and Construction 1999 by the Society of Building Science Educators (SBSE) to address site and building issues. Their work acknowledged John Tillman Lyle's idea that sustainable design is merely breaking even, while regenerative design renews earth resources [20]. On a larger scale, Pliny Fisk's work on EcoBalance land-use planning and design method employed the principle of life cycles as a framework for sustaining basic life supporting systems, balancing human needs with their ability to manage the environment using technologies for augmenting natural processes [26].

Emergence of Regenerative Development and Design as Distinct Disciplines In 1996, John Tillman Lyle published *Regenerative Design for Sustainable Development*, the first comprehensive articulation of, and handbook for, regenerative design [11]. Written as a practical guide to the theory and design of regenerative systems, it laid out the framework, principles, and strategies for a design technology aimed at reversing the environmental damage caused by what Lyle called industrial land-use practices. The book reflected the continuing evolution of the thinking he had been pursuing as a landscape architect, architect and educator. He established the Center for Regenerative Design at California State Polytechnic University, Pomona to test, demonstrate, and further evolve this technology.

Deeply concerned about conventional industrial development's resource depletion and environmental degradation – consequences embedded in "the design of our twentieth century landscape," Lyle believed that at the core of growing environmental crises lay the simplification of living systems caused by "paleo" design and technologies (a term he adopted from Patrick Geddes to depict their relative crudity). "Where nature evolved an ever-varying, endlessly complex network of unique places adapted to local conditions," he wrote, "…humans have designed readily manageable uniformity." This creates relatively simple patterns and forms designed to be easily replicable anywhere. Most important, in his view, was the replacement of nature's continual cycling and recycling of materials and energy – processes "core to the earth's operating system" – with one-way linear flows from source to sink. "Eventually a one-way system destroys the landscapes on which it depends," Lyle observed. "The clock is always running and the flows always approaching the time when they can flow no more. In its very essence, this is a degenerative system, devouring its own sources of sustenance." The degenerative patterns caused by these linear, one-way flows he believed, demanded a fundamentally different approach that he named regenerative design. Accordingly, Lyle defined regenerative design as the replacement of linear systems of throughput flows with "cyclical flows at sources, consumption centers, and sinks." The resulting systems provide for "continuous replacement, through (their) own functional processes, of the energy and materials used in their operation" [11].

Lyle died just 4 years after publication of *Regenerative Design for Sustainable Development*. While he called redesign of the degenerative systems created by industrial linear flows as the "first order of work," it is clear from the larger body of his work and other writings [19] that he saw regenerative design as encompassing far more than this basic operational goal, as fundamental as it was. While much attention has been given to his models and techniques for designing self-renewing resource and energy flows, Lyle always saw the heart of his work, and the work of regenerative design, as the conscious design of whole ecosystems. His concern with the importance of developing a different nature of thinking as the basis for regenerative design, which was addressed in introductory chapters of the book, was also left without further development. Unfortunately, the narrow definition of the term regenerative as simply "self-renewing" came to define the focus of regenerative design for many architects and landscape architects.

In 1995, the authors of this chapter and the Regenesis Collaborative Development Group began developing the theoretical and technological foundation for regenerative development – enabling human communities to coevolve with the natural living systems they inhabit while continuously regenerating environments and cultures. Regenesis founders had practiced biocentric design, inspired by natural processes, in a variety of arenas for a number of years and knew the power of this approach. They agreed that development projects needed to be sources of ecological health, even "engines of positive or evolutionary change for the systems into which they are built" [27]. While agreeing with the ends of ecological sustainability, they felt that the primary cause driving unsustainable patterns was not being addressed by ecological design systems. They saw environmental problems as symptoms of a fractured relationship between people and the living web of nature, and argued that the core issue was cultural and psychological, rather than technological. Like Lyle, they believed that addressing this issue required a fundamental transformation in how humans saw their relationship and role with regard to the planet – moving from the current view of standing apart from and using (or protecting) nature to seeing a "coevolutionary whole, where humans exist in symbiotic relationship with the living lands they inhabit" [28].

For regenerative design to take hold and be successfully applied, they reasoned, a radical shift in thinking and understanding would be required among design professionals, stakeholders, and all the human inhabitants of a place. They proposed the term regenerative development for the more comprehensive work of creating the conditions and building the capacities required for achieving this shift, with the aim of making development a source of harmonious integration with nature [27, 29].

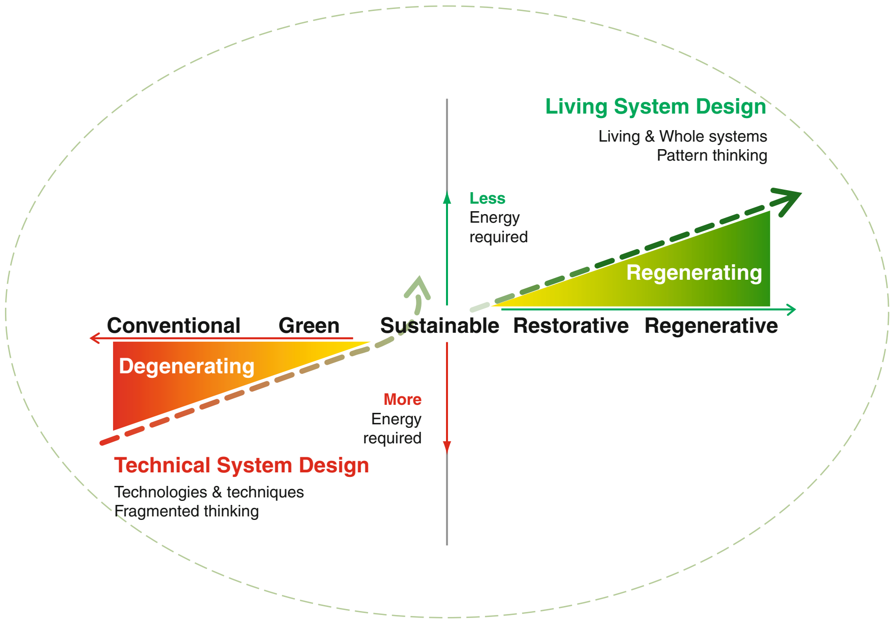
Regenerative Development and Design–Redefining Sustainability

Introduction

Sustainable development and design has been described as falling broadly into two streams – one primarily technical and engineering based (technological sustainability) and the other based in ecology and living systems principles (ecological sustainability) [4, 7]. Green or high-performance building, sometimes called eco-efficient design, emerged out of the first stream, and regenerative development and design out of the second. Green building, like the conventional building field before it, defined the built environment as "all the structures people have built when considered as separate from the natural environment" (MacMillan Dictionary). It defined a sustainable built environment as one that is resource efficient and has minimal or neutral environmental impact. While that definition is evolving, the primary aim of green building continues to be increasing the efficiency of energy, water, and material use while reducing local and global impacts on the natural environment.

However, as Sarah Jenkin and Maibritt Pedersen Zari note in their 2009 research paper, "Rethinking the Built Environment," "The definition of a sustainable built environment is changing rapidly. While aiming for neutral or reduced environmental impacts in terms of energy, carbon, waste or water are worthwhile targets, it is becoming clear that the built environment must go beyond this. It must have net positive environmental benefits for the living world" [10].

The rising field of regenerative development and design, which emerged from the ecological stream, is not only leading the charge to redefine sustainability but also redefining what the built environment encompasses and what its role must be. Advocates of



Regenerative Development and Design. Figure 1
Graphic contrast of Technical System Design and Living System Design. © Regenesis Group. Reprinted with permission

a regenerative approach to the built environment believe that a much more comprehensive, deeply integrated, and whole-systems approach is needed. They propose that eco-efficient design technologies and strategies be integrated within an ecologically based approach that reverses the degeneration of both the earth's natural systems and the human systems that inhabit them. The methodology of this approach focuses on the development of human settlements that partner with natural systems and processes to actively regenerate the health of their place as a whole and the spirit of the people who inhabit it (Fig. 1).

The philosophical and technical foundations for regenerative development and design as a distinctive field within ecological sustainability were laid in the 1990s, though they draw from scientific and technological advances reaching back into the early part of the last century (see "Chronology"). The practices emerging from that body of work are still evolving and expanding to cover an increasingly broad and sophisticated spectrum of sustainability concerns. Held together by a common philosophical core, they extend beyond the traditional aspects of design to address the different nature of thinking and interactivity that is required to design and engage in a regenerative process.

While regenerative approaches are attracting growing interest among sustainability design practitioners, transitioning from green building to a regenerative practice has presented a number of challenges. The holistic and deeply integrated nature of the regenerative approach does not lend itself to a "menu approach" – picking one or two regenerative technologies without understanding the underlying principles that assure a regenerative outcome. Another challenge is reconciling the two radically different worldviews shaping technological and ecological sustainability within the way one's practice is carried out. Few architects and engineers are familiar with, let alone trained in an ecological paradigm. Yet as David Orr notes:.

- *Ecological problems are in many ways design problems: our cities, cars, houses, and technologies often do not fit in the biosphere. Ecological design requires the ability to comprehend patterns that connect, which means looking beyond the boxes we call disciplines to see things in their larger context. Ecological design is the careful meshing of human purposes with the larger patterns and flows of the natural world; it is the careful study of those patterns and flows to inform human purposes. Competence in ecological design requires spreading ecological intelligence—knowledge about how nature works.* [30]

Still, another challenge lies in the lack of a universally agreed upon definition for regenerative development and design and a tendency to blur or confuse regenerative approaches with the range of other design systems that emerged in pursuit of ecological sustainability in the 1990s.

This confusion around the distinctive nature of regenerative development and design has been due in part to being an emerging field lacking universal understanding of the meaning of regeneration, especially as it applies to design of the built environment. The distinction between regenerative development and regenerative design must also be further clarified if this field's potential contribution to sustainability is to be fully realized.

Overview: Ecological Sustainability and Regenerative Development and Design

Ecological Sustainability

Ecological sustainability has been defined as the "capacity of ecosystems to maintain their essential functions and processes, and retain their biodiversity in full measure over the long-term" (www.businessdictionary.com). While accurate and straightforward, the seeming simplicity of this definition is deceptive. To understand and then deliver what is required to "maintain" and "retain" requires first understanding the nature of ecosystems and the nature of the ecological world in which they exist. That, in turn, requires understanding the ecological perspective – the use of ecological concepts from biology as a metaphor for understanding and designing environments.

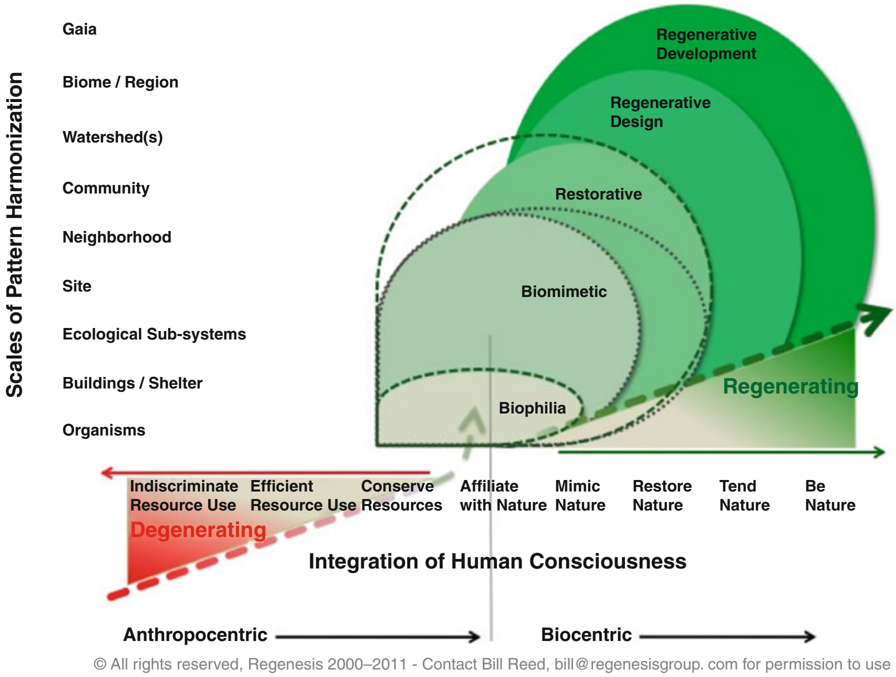
All development of the built environment involves changing the landscape and, perforce, the natural systems embedded within it – modifying and adapting them for human purposes. The design of that change is ultimately based on the designer's understanding of the "nature of nature"– how nature works and, concomitantly, humans' relationship to it. That understanding, in turn, is shaped by the fundamental model or paradigm held by the larger culture – the metaphor used to depict how the world works. In the same way, technologies reflect a culture and how it understands nature [7, 11, 25].

The divergent definitions of ecological and technological sustainability can be attributed in large part to their being grounded in very different worldviews. Ecological sustainability as a field and the design systems within it emerged from the profound shift in worldview that occurred over the last century as a result of advances in both the physical and biological sciences. Fritjof Capra has described this as a shift from the mechanistic worldview of Descartes and Newton. In that paradigm, the dominant metaphor for understanding the world (and all organisms within it) was that of a machine composed of separate parts. In contrast, the ecological worldview sees the world as a self-organizing, continuously evolving, interdependent web of living systems, and the concept of ecosystem is the dominant metaphor for understanding its workings. The ecosystem concept, as it has been evolved and informed by living systems science, has been particularly influential in shaping ecological and regenerative understanding of the world and the role of humans within it, with profound implications for sustainability and development [5, 14, 15].

The industrial era metaphor of machine was particularly influential in shaping much of the built environment in the developed world and continues to play a significant role even today. By the first decade of the twenty-first century, however, Le Corbusier's image of the modern house as a "machine for living" was being challenged by the image of living buildings and communities as ecosystems.

As the ecosystem emerged as a new "governing concept of relationship between humanity and nature" [14], it confronted some of the most basic premises of the technologies, processes, and goals of the design field at the time, including the role of buildings, the definition of the built environment, the role of designers, and even the role of humans on the planet. As designers concerned about sustainability began to explore the implications of this new paradigm, it became clear that new ways of thinking and working, along with new forms of technology and new standards of ecological performance were required. The ecological sustainability stream, and within that stream, regenerative development and design, grew out of the work of the pioneering designers, educators, and scientists who took up the challenge of changing their design practice, themselves, and ultimately, their field in order to meet these requirements.

While many have written about different aspects of ecological sustainability during and since the 1990s,



Regenerative Development and Design. Figure 2
Levels of Ecological Strategies for Sustainability. © Regenesis Group. Reprinted with permission

some of the most comprehensive articulations of the key premises that shaped the distinctive character of the broader field as a whole can be found in the writings of Sim Van der Ryn, Stuart Cowan, David Orr, and Fritjoff Capra [4, 5, 7, 30].

Regenerative Development and Design Overview

A number of ecological strategies for sustainability were developed during the 1980s and 1990s that were organized around the core set of philosophical, theoretical, and scientific concepts that underlie the ecological perspective of reality. All were aligned around a commitment to net positive goals for the built environment and to integrate human structures, processes, and infrastructures with natural living systems to that end. They differed in the systemic scope they encompassed, falling into four broad categories along a spectrum of comprehensiveness (Fig. 2).

1. Biomimetic – Cradle to Cradle and Biomimicry are design philosophies that fit into this category:

   Biomimetic approaches look to nature as inspiration. It is a *functional* approach that uses nature – its forms and its processes – as a model for humans to follow – an anthropocentric perspective. Technical product design, buildings, manufacturing processes, agriculture, and human activity will function best and be more in harmony with ecological processes if nature is used as a model and guide. Nature's services and techniques are generally much more effective and certainly more sustainable than technical engineering approximations [31].

   The principles guiding biomimetic thinking are essentially derived from an ecological understanding of how life works and provide a conceptual starting point to move into more whole and regenerative systems scope.

2. Biophilia – A general term, meaning "urge to affiliate with other forms of life" [32].

   As a design philosophy, biophilia is *relational* in its approach – it is somewhat passive in its engagement with life and is anthropocentric in its purpose. It acknowledges that humans will, if given a choice between nature and a human-made context, choose an environment or situation that utilizes, or is in contact with, living systems and their processes. Human health is positively influenced in relation to life and diminished if separated from living system connectivity. The design fields that use biophiliac approaches consciously use Literal Connections to natural features and elements; Facsimile Connections in terms of the use of nature imagery and materials; and Evocative Connections that use the qualities and attributes of nature in design such as sensory variability, prospect and refuge, serendipity, discovered complexity [33].

3. Restorative – Reestablishes the self-organizing and evolving capability of natural systems.

   This is an approach that acknowledges that humans have a role to play. It is more highly *integrated* than biomimetic approaches and more *active* than biophilic approaches – yet it generally is an episodic and finite engagement. This approach typically intervenes on an initial basis to reestablish the health of a subsystem of an ecosystem and community – such as wetlands, woods, riparian corridors, beach dune systems, social systems, and so on. It is a biocentric approach. When the intervening human role is finished, however – once the capacity of the system to self-organize is set in motion – the humans leave the engagement and are expected to [34].

4. Regenerative

   Acknowledges that humans are "nature," and there is greater hope of evolutionary potential in a state of intentional interrelationship. Humans have a positive role to play in nature. In order to create sustained ecological health, humans must evolve a conscious and *integral* interrelationship where humans and nature are in a mutually beneficial being and becoming relationship – one that is always aware of evolutionary potential. It is a fully conscious awareness that the health of an ecosystem is dependent on human health and human health is dependent on the health of the whole ecology. It is coevolutionary. This might be termed a process of *biobecoming* – the development of a whole system of interrelated living consciousness – a new mind. "Design inevitably instructs us about our relationships to nature and people that makes us more or less mindful and more or less ecologically competent. The ultimate object of design is not artifacts, buildings, or landscapes, but human minds" [4].

M. Kat Anderson supports this way of being in "Tending the Wild": *Wilderness is a negative label for land that has not been taken care of by humans for a long time...California Indians believe that when humans are gone from an area long enough, they lose the practical knowledge about correct interaction, and the plants and animals retreat spiritually from the earth or hide from humans. When intimate interaction ceases, the continuity of knowledge passed down through generations, is broken, and the land becomes "wilderness"* [35].

Together, regenerative development and design provide a framework for creating, applying, adapting, and integrating a blend of modern and ancient technologies to the design, management, and continuing evolution of sustainable built environments, accomplishing positive ecological and social results that include:

- Improving the health and vitality of human and natural communities – physical, psychological, economic, and ecological.
- Producing and reinvesting surplus resources and energy to build the capacity of the underlying relationships and support systems of a place needed for resilience and continuing evolution of those communities.
- Creating a field of caring, commitment, and deep connection to place that enables the changes required for the above to take place and to endure and evolve through time [10, 28].

The first comprehensive articulation of the theoretical and practical basis of regenerative approaches to the built environment emerged separately for regenerative development and regenerative design in the mid-1990s from two separate sources – the work of Regenesis Collaborative Development Group and John Tillman Lyle. Their respective bodies of work each reflected a convergence of disciplines in addition to architecture including, landscape ecology, geohydrology, landscape architecture, permaculture, regenerative agriculture, general systems theory and cybernetics, living systems theory and thinking, and developmental psychology.

Regenerative development and design, as articulated by Regenesis and Lyle, recognizes that "humans, human developments, social structures and cultural concerns are an inherent part of ecosystems" [10], making humans integral and particularly influential participants in the health and destiny of the earth's web of living systems. According to this view, the sustainability of the real estate development industry, which works directly on these webs, is largely determined by whether humans participate in them as partners or as exploiters [11, 25, 27, 28, 36, 37].

In his paper, "New Context, New Responsibilities: Building Capability" [38], Ray Cole articulated some of the key implications of a regenerative approach, including:

- Seeing the responsibility of design as "designing the 'capability' of the constructed world to support the positive coevolution of human and natural systems" versus designing "things" (buildings, infrastructure, etc.) and defining sustainable buildings as "buildings that can support sustainable patterns of living."
- Emphasizing the "role of building in positively supporting human and natural *processes*" versus "building as *product*."
- Positioning "building as central in creating higher levels of order and, as such, creating increased variety and complexity."
- Seeing the building as within and connected to a larger system – place, shifts "the current emphasis of greater energy self-reliance at the individual building level" to "opportunities for positive connections and creative synergies with adjacent buildings and surrounding natural systems."

A Note on the Distinction Between Regenerative Development and Regenerative Design For ecological sustainability to succeed, it requires a far broader and deeper scope of engagement than an individual building or even community design [39]. Yet the structure of the development and construction industry, for the most part, works to narrow the designers' role and scope, often as a result of decisions made before the design process even begins. Regenerative development was developed, in part, to address this concern. Regenerative approaches view development and design as two distinct yet synergistic processes, both of which play an essential role in ensuring that greater scope, neither of which is sufficient without the other.

The following dictionary definitions provide insight into the different roles of development and design:

Development: *O.Fr. desveloper, "an unfolding, bringing out the latent possibilities," from des- "undo" + veloper "wrap up"* a state in which things are improving; the act of improving by expanding or enlarging or refining; progression from a simpler or lower to a more advanced, mature, or complex form or stage; an unfolding; the discovering of something secret or withheld from the knowledge of others; disclosure.

Design: *L. designare "mark out, devise," from de- "out" + signare "to mark,"* an act of working out the form of something; to create or contrive for a particular purpose or effect.

Jenkin and Pedersen Zari, in their study, "Rethinking the Built Environment," write that "Regenerative development . . . investigates how humans can participate in ecosystems through development, to create optimum health for both human communities (physically, psychologically, socially, culturally and economically) and other living organisms and systems." They describe regenerative development as defining the desired outcome, and regenerative design as the means of achieving it. In contrast, John Tillman Lyle [25] defined design within the context of the built environment as giving form to physical processes [ref], and regenerative design as the replacement of linear systems of throughput flows with "cyclical flows at sources, consumption centers, and sinks." The resulting systems provide for "continuous replacement, through (their) own functional processes, of the energy and materials used in their operation" [11].

Regenerative development works at the intersection of understanding and intention, generating the patterned, whole-system understanding of a place, and developing the strategic, systemic thinking capacities and the stakeholder engagement required to ensure the design process achieves maximum systemic leverage and support. To that end, it integrates building, human, and natural development processes within the context of place. Regenerative development also creates an environment that greatly enhances the effect and effectiveness of restorative and biomimetic designs.

The roles of regenerative development, more specifically, are to:

1. Determine the *right* phenomena to work on, or to give form to, in order to inform and provide direction for regenerative design solutions that can realize the greatest systemic potential.

2. Build a field of commitment and caring in which stakeholders step forward as cocreators and ongoing stewards of those solutions.

Regenerative design then follows directly to offer a system of technologies and strategies based on an understanding of the inner working of ecosystems. Regenerative design solutions regenerate rather than deplete underlying life support systems and resources, are grown from the uniqueness of place, and work to integrate the flows and structures of the built and natural world "across multiple levels of scale, reflecting the influence of larger scales on smaller scales and smaller on larger" [40].

Regenerative Approaches to Sustainable Development and Design – Key Framework Premises and Practice Methodologies Overview

Key Premises

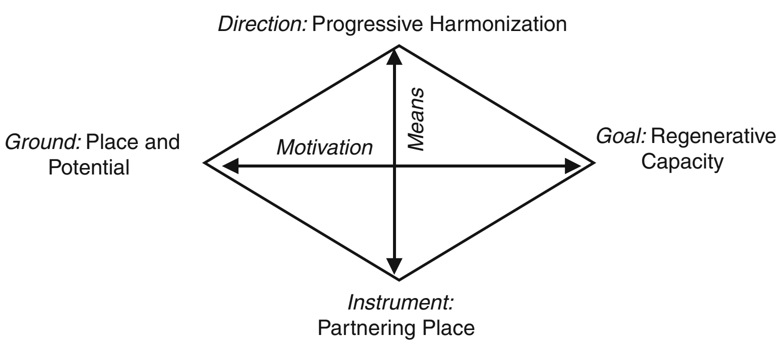
The following four premises are drawn from the work of Regenesis and Lyle. They offer key elements for framing regenerative approaches [11, 25, 27, 29, 37]. The four premises work as a system to integrate and align motivation and means, providing the framework within which methodologies and approaches from other ecological design systems can be integrated into a regenerative practice (Fig. 3). The first two define and shape motive and motivation in a regenerative project. The last two relate to how a project is carried out to ensure that ends and means stay congruent and that the process stays on course toward a regenerative result.

1. *Place and potential* – Understanding and conceptualizing right relationship to place. Starting with the richest possible understanding of the evolutionary dynamics of a place in order to identify the potential for realizing greater health and viability as a result of human presence in that place [41].
2. *Goals focus on regenerative capacity.* Regenerative project goals are defined by the capacity that must be developed and locally embedded to support ongoing coevolution of the built, cultural and natural environments, and the humans who utilize and tend to them toward higher (more complex, diverse, and generative) levels of order for all their constituent members as well as for the larger systems they are a part of and depend on [12, 37].
3. *Partnering with place.* Implementing a regenerative project requires taking on a new role, moving from a "builder of systems we control" to a gardener, working in partnership with a place and its processes [42].
4. *Progressive harmonization.* Regenerative approaches seek to catalyze a process of continually increasing the pattern harmony between human and natural systems and require indicators and metrics that can track dynamic, holistic, and evolving processes [43].

Place and Potential

- Potential: "the inherent capacity for growth, development or coming into being." (American Heritage Dictionary of the English Language)

William McDonough often describes design as an expression of human intention. Both that intention and the resultant design, however, are shaped by the



Regenerative Development and Design. Figure 3
Framework depicting key premises and processes characterizing regenerative approaches. © Regenesis Group. Reprinted with permission

potential the designer sees and seeks to realize for a particular project. Regenerative potential is defined as the ability to leverage human interventions to achieve greater systemic health through time for the place they occupy and depend on [27].

Many projects fail to achieve a regenerative effect because the potential they target is too limited – focused on an element or a problem without seeing its systemic connections. Others fail because they seek to realize potential defined by human ideals but fail to recognize and are thus unable to align with the essence of a place and the larger patterns of life that make it work. When a project is grounded in a rich patterned understanding of its place and a vision of its role and potential within that place guides its design, even small interventions can ripple out into large systemic transformations – what Curitiba's long-time mayor Jaime Lerner called "urban acupuncture" [44], with ecological as well as social and economic ramifications.

"Place" in regenerative development is alive, a living system or entity that is ". . .a unique constellation of patterns nested within patterns, interwoven with other patterns in families and guilds and social relationships, all endlessly changing, cycling, evolving and building to greater levels of complexity over time . . . an incredibly dynamic and complex being" [43]. A unique, multilayered dynamic network of natural and human ecosystems within a geographic region, this network forms a socioecological whole that is the result of complex interactions through time between and within its constituent ecosystems. The natural ecosystems include wildlife and vegetation, local climate, mineral and other deposits, soil, water geologic structures, etc.; human ecosystems include distinctive customs, expressions of values, economic activities, forms of association, ideas for education, traditions, physical artifacts such as buildings and constructed infrastructure, etc. [11, 28, 36, 37, 45, 46].

Regenerative Capacity: *Defining Goals for Realizing Regenerative Potential* The central element for regenerative development and design is the performance not of a single building, but rather of its living context – the unique socioecological system or "place" in which the building is just one of many interdependent and interactive elements and dynamics. Within that context, regenerative goals are set, and performance measured in terms of the intended contribution of the built environment to the regenerative capacity of that larger living context – (i.e., its capacity to realize and express more of its full potential as a source of increasingly healthy life for all its constituent members as well as for the larger systems it is a part of and depends on).

Characteristics of regenerative goals include:

- Place-sourced and place specific.
- Evolutionary, going beyond improving current systemic performance (what is often called restorative) to embedding into the system the capacity to continue to improve performance through time and through varying environmental conditions.
- Goes beyond functional performance goals. Recognizing "human aspiration and will as the ultimate sustaining source of our activities" [28], they address qualitative and spirit dimensions that shape the quality and degree of caring humans bring to their place and its capacity to continue to thrive.
- Focus on the processes physical structures enable as central.

Growing Capacity Versus Producing Things Regenerative projects set place and project specific goals that address all three aspects of regenerative built environments:

- Operational capacity.
- Organizational capacity.
- Aspirational capacity.

Operational capacity goals: Operational goals focus on systemic functional effectiveness in growing the potential of the underlying resource base – energy, materials, and support systems that enable the evolution of life in a place. Regenerative projects set goals for ensuring that the energies and nutrients flowing through it are used and invested optimally to grow the health of the system and all the life it supports.

Organizational capacity goals: Organizational capacity focuses on "who" a place is and addresses two dimensions – what is core to how this place works as a living system (what one can "mess" with and what one cannot) and what is the core qualitative character (its essence or distinctiveness, not data alone) or nature that humans can connect to at a heart level.

Goals for this aspect deal with how to utilize the built environment and the design process to both illuminate and enhance the distinctive character of a place as something to be cherished. Historic codes and zones are often used to this end, but they tend to focus on surface appearance rather than essence, and over time, the code and its restrictions come to take the center stage, overshadowing the living core of the place they intended to protect [38].

Aspirational goals: Growing the systemic regenerative capacity of a place requires an integration of human aspirations with the distinctive ecosystems of that place and their drive to evolve their own health and generativity. This means harnessing inherent human creativity and aligning it with the creativity of nature and creating opportunities for people to experience themselves as able to make significant and meaningful contributions to their place [11, 47].

Partnering with Place – A New Role for Humans and Buildings In an ecological paradigm, sustainability requires a fundamental shift in how humans conceive of and carry out their role on the planet. In the words of Joshua Ramo, people must "change the role we imagine for ourselves from architects of a system we can control and manage to gardeners in a living, shifting ecosystem. For hundreds of years now we have lived in our minds as builders: constructing everything from nations to bridges . . . In a revolutionary age, with rapid change all around us, our architects' tools are deadly. It is time for us to put them down and follow (Nobel Laureate Friedrich von) Hayek's injunction to live and to think as gardeners."– gardeners who see themselves as partners in coevolution with the living system in which they work, cultivating "growth by providing the appropriate environment, in the manner a gardener does for his plants" [42, 48].

Successful regenerative development ultimately requires all the stakeholders in a place, not just the development/design team to move from the role of "builder" to "partner-gardener," with the first step a different nature of understanding that enables people to see the places they inhabit as alive.

A whole-systems assessment looks at a wide range of patterns covering multiple scales of systems and a number of different facets. The place intelligence it develops is a resource that can be mined to inform each stage of design to help ensure that the patterns generated by the project harmonize with the larger patterns of place. Another nature of understanding, however, is required to generate the experience of connection and caring that creates a relationship of partnership with a place. This understanding conveys "who" a place is as a living being in addition to how it functions. Every living system – whether a person, a tree, or a place – has an ongoing and distinctive core from which it organizes the complex arrays of relationships that produce its activities, its growth, and its evolution. Being able to grasp and share the distinctive core or *essence* of a place among and between the design team and local stakeholders provides an enduring basis for strong partnering relationships; in the same way, it builds strong human partnerships.

► A New Way of Thinking:

Learning how to apply a regenerative approach begins not with a change of techniques but rather with a change of mind—a new way of thinking about how we plan, design, construct, and operate our built environment [27].

Growing stakeholders and designing and constructing projects that can work as "place gardeners" requires bringing and developing whole-systems thinking that is able to and capable of comprehending and ordering and organizing the systemic complexity and dynamism of a living place and its multiple scales of nested systems, interactions of multidisciplinary teams over extended periods, and extensive local stakeholder participation [14, 15, 49]. This nature of systems thinking is characterized by:

- Being grounded in ecoliteracy and pattern literacy. Ecoliteracy applies an understanding the fundamental principles that govern how living systems work to specific situations and conditions. Pattern literacy involves being able to read, understand, and generate appropriate patterns that harmonize with and enable a place and its inhabitants to more fully realize what they can be [43].
- Requiring the practitioners to see what they are working on as a system of energies or life processes rather than as things – illuminating the constant reaching toward being more whole and being more alive inherent in living systems that is the fuel for regeneration [29, 50].

- Enabling a diversity of participants to grow their own systems thinking capacity in order to take on more challenging, value-adding roles [21, 50].

A new way of working: Regenerative development and design does not end with the delivery of the final drawings and approvals, or even with build out of a project. The responsibility of a regenerative designer includes putting in place, during the development and design process, what is required to ensure that the ongoing regenerative capacity of the project, and the people who inhabit and manage it, is sustained through time. Regenerative development employs *Developmental Design Processes.* They encompass integrative design (integrative, interdisciplinary beyond traditional building disciplines, open, and participatory) [51] and go beyond to embed self-managed learning processes into the work of conceptualizing, designing, constructing, managing, and evolving regenerative projects. They integrate the traditional focus of organizing for task accomplishment with the development of new thinking capacities required to design processes not things, make ecologically sound place-appropriate decisions, and create the being connection to and emotional resonance with place that generates the will required to follow through on those decisions.

Progressive Harmonization The "pole star" or overarching source of direction for regenerative projects derives from the ultimate effect every regenerative project seeks to achieve: an enduring and mutually beneficial relationship between the human and natural systems in a particular place. Pattern is the language of relationship, and regenerative development and design in a living system is a process of patterning human communities to align with the energetic patterns of a place in a way that both humans and the place coevolve. Christopher Alexander was speaking of pattern harmony when he wrote, "When you build a thing, you cannot merely build that thing in isolation, but must also repair the world around it, and within it, so that the large world at that one place becomes more coherent, and more whole; and the thing which you make takes its place in the web of nature, as you make it" [52]. While his initial work focused primarily on the pattern relationship between a building and the human community and life surrounding, his later work has increasingly encompassed all living systems. Wendell Berry, in his essay Solving for Pattern, speaks to creating pattern harmony between human communities and activities and the biosphere they take place in [53]. "A bad (design) solution is bad," Wendell Berry notes, "because it acts destructively upon the larger patterns in which it is contained. . . most likely, because it is formed in ignorance or disregard of them. A good solution is good because it is in harmony with those larger patterns . . . A bad solution acts within the larger pattern the way a disease or addiction acts within the body. A good solution acts within the larger pattern the way a healthy organ acts within the body" [53].

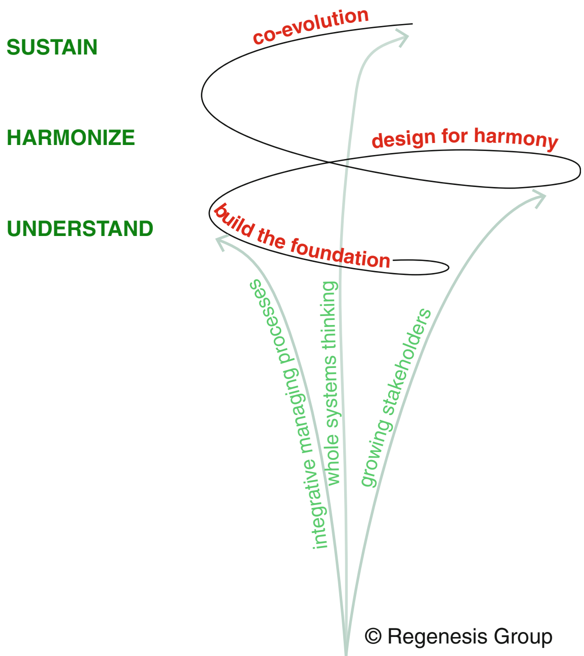
Pattern harmony, however, is not a stable state; a good solution today may become a bad one in a few years, so solving for pattern requires a progressive rather than one-time harmonization, a continuous repatterning. Theoretical biologist Stuart Kauffman called this mutually beneficial relationship "co-evolving mutualism" – co-evolving because "its ecosystems are always in the process of self-organization and reorganization, increasing in complexity, definition, and information content" [25, 54, 55].

Practice Methodologies

The following is an example of how these premises can translate into a regenerative practice. The methodologies were developed from over 15 years of fieldwork by Regenesis during which collaborative members explored, practiced, and evolved regenerative development. The diagram in Fig. 4 was developed as a depiction of the essential elements of this practice – three phases and three developmental processes that are considered key to creating and sustaining an evolutionary spiral, growing systemic capacity as it actualizes a project.

The Three Key Steps:

Understand the Relationship to Place: Integral assessment – a whole-systems (cultural, economic, geographic, climatic, and ecological) assessment of site and place as living systems lays the foundational understanding and thinking required to see how humans can enable the health and continuing evolution of the place and themselves as a part of it. A Story of Place® is codeveloped with the client and/or community. It uses the power of



Regenerative Development and Design. Figure 4
Regenerative practice methodology framework.
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storytelling to articulate the essence of a place, how it fits in the world, and what the role of those who inhabit it can be as collaborators in its evolution.

Designing for Harmony with Place: Translates this understanding into design principles and systemic, integrated plans, designs and construction processes that optimize the presence of people in a landscape by harmonizing with the larger pattern of place. Buildings and infrastructure improve land and ecosystems, and the unique attributes of the land improve the built environment and those who inhabit it. Synergy with the land and ecosystems leverages the effectiveness of green design features and technologies and lowers costs while improving ecosystem health and productivity.

Co-Evolution: "*. . .sustainability means maintaining the dynamic potential for further evolution. Living systems survive by maintaining a condition of dynamic equilibrium with the environment through constant change and adaptation. In the game of evolution, equilibrium is death*" *Urban Sustainability Learning Group* [56]. This phase unfolds from the work of the previous two phases. If they have succeeded in creating a culture of coevolution in and around the project, and not just a physical product, its effect can be seen even before final build out. The role of designer becomes one of resource, providing processes and methods for sustaining the connection to place as a context that enables owners, managers and maintenance contractors, and community stakeholders to recognize and incorporate new social, economic, and ecological opportunities as their place evolves.

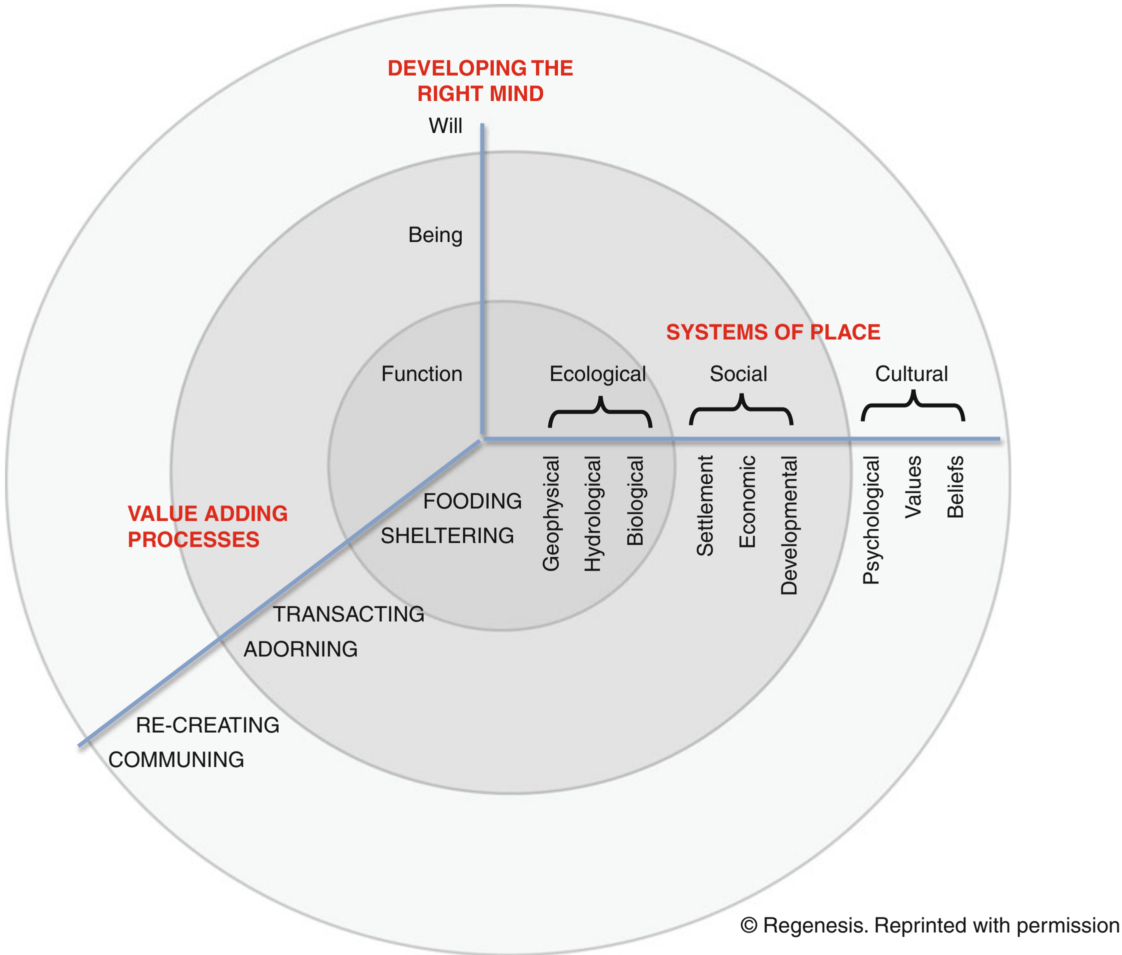
The Three Key Determining Factors: Success in the above three steps is determined by how one thinks, how one identifies harmonies and harmonizes the human role, and how one engages stakeholders *throughout* the planning and development process. Specifically, whether one:

- *Applies whole-systems thinking* to the design, planning, and decision making processes.
- *Manages integration and harmonization* across disciplines, between phases and team members and local stakeholders.
- *Grows stakeholders* understanding and appreciation of the place and the new potential offered and their capacity to be increasingly effective partners with the whole system of evolving life.

The following are examples of the thinking and practice frameworks and methodologies applied within the three phases and processes, some developed by Regenesis, some drawn from other ecological design systems.

Understand the Relationship to Place Principles from permaculture and Biomimicry are helpful in developing specific land use, building, and infrastructure design strategies.

Permaculture: *As* a design system rooted in the ability to discern the patterns that are structuring both natural and human systems and to generate new patterns that weave the human and natural together into a dynamic whole, permaculture assessment methodologies provide a source for developing holistic site assessments. *Pattern as Process*, an article by Regenesis



Regenerative Development and Design. Figure 5
Integral Assessment Scope framework. Used as a means of illuminating the core patterns structuring a place as the basis for "mapping" their dynamic and evolving interrelationships. © Regenesis Group. Reprinted with permission

principal Tim Murphy and Vickie Marvick, provides a detailed description of their method for understanding and interpreting the patterning of a site and its place [43].

Assessment Scope Framework for Pattern Understanding (Fig. 5): The challenge in any assessment process is to ensure that the scope being assessed is whole enough to encompass the interweaving of human and natural systems, dynamics and flows that shaped the distinct character of a place. Regenesis developed the following framework as a means of illuminating the core patterns structuring a place as the basis for "mapping" their dynamic and evolving interrelationships. These include:

- The ecological, social, and cultural systems creating and managing the conditions that shape how life expresses itself in a place.
- The value-adding processes life engages in within the context of those conditions and how they influence and are influenced by them.
- The developmental implications and opportunities for how individuals (people and buildings) can enable the health and continuing evolution of the place and themselves through how they function, the qualitative state of being they seek and enable, and what they value and express will toward (Adapted from a framework developed by Charles Krone as part of his thinking technology [8]).

Essence Understanding: The essence understanding that conveys "who" a place is as a living being emerges from the whole-systems assessment. Questions used to reveal the essence include: What is at the core of a system, around which it is organized? What is the web or larger context of reciprocal relationships within which it is embedded since all systems are comprised of smaller systems and part of larger systems? And what is the potential inherent in a living system that it is attempting to live out since this is the fuel for regeneration – this constant reaching toward being more whole, being more alive?

- Simple example of patterns and the essence of a system: [51]

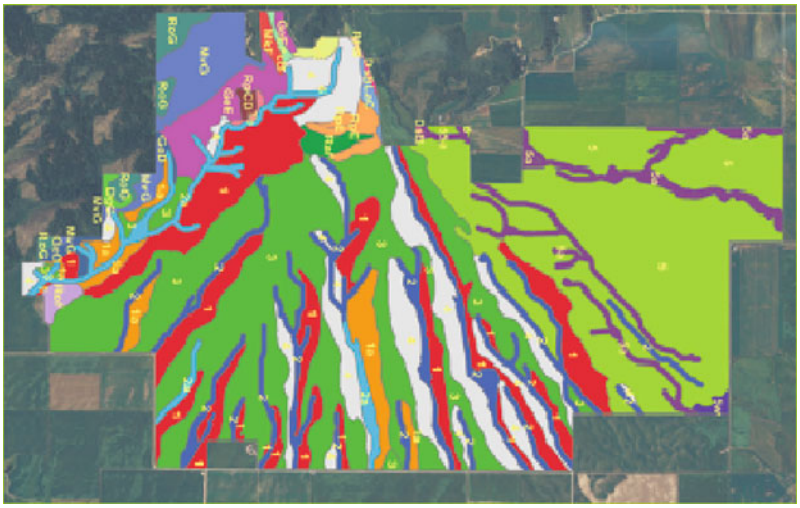
  Mahogany Ridge, Idaho, USA: *A reductionist approach or an approach that abstracts life into a checklist might state that nothing should be built on existing farmland. This might be a good principle if the agriculture system was truly symbiotic with nature. In this case, farming had nearly destroyed three distinct ecological systems. An integral assessment looked for possible patterns of life that allowed for high levels of relationship between species and ecological niches.*

  The aerial photo in Fig. 6 depicts approximately 3,500 acres of current farmland along the eastern edge of the Big Hole Mountains (just west of the Grand Tetons) that was being considered for development. Originally, these mountain watercourses and alluvial fan supported beaver, otter, native cutthroat trout, salmon, turkeys, grouse, and mega-fauna, such as deer, elk, moose, and bears. These animals were all responsible for carrying nutrients back upstream into the mountains to feed the forest and diversify the terrestrial and riparian ecosystem. Pioneers of European descent arrived in this place 100 years ago and used row-crop agriculture techniques to farm on this alluvial fan. As a result, ninety percent of the water from the Big Hole Mountains (in picture) was being used for agricultural purposes (spray irrigation), the salmon were no longer breeding in the river, the Yellow Tail cutthroat trout were in species decline, the river was polluted from overloads of nitrogen, and the upstream forests were in decline.

  The area farmers were going out of business or bankrupt due to the short growing season. The farms, in the past, had been used to support local needs. Twenty to forty acre-per-home zoning is planned as the alternative to large farms.

  Looked at closely, this photo in Fig. 6 reveals that farming was superimposed on top of this alluvial fan between the stream in the mountain valley

Regenerative Development and Design. Figure 6
Aerial photo of Mahogany Ridge Resort Community site



Regenerative Development and Design. Figure 7
Soil map of Mahogany Ridge site showing alluvial fan patterns

(top center of the photograph) and the river. The soils mapping indicated in Fig. 7 reveals the pattern more clearly.

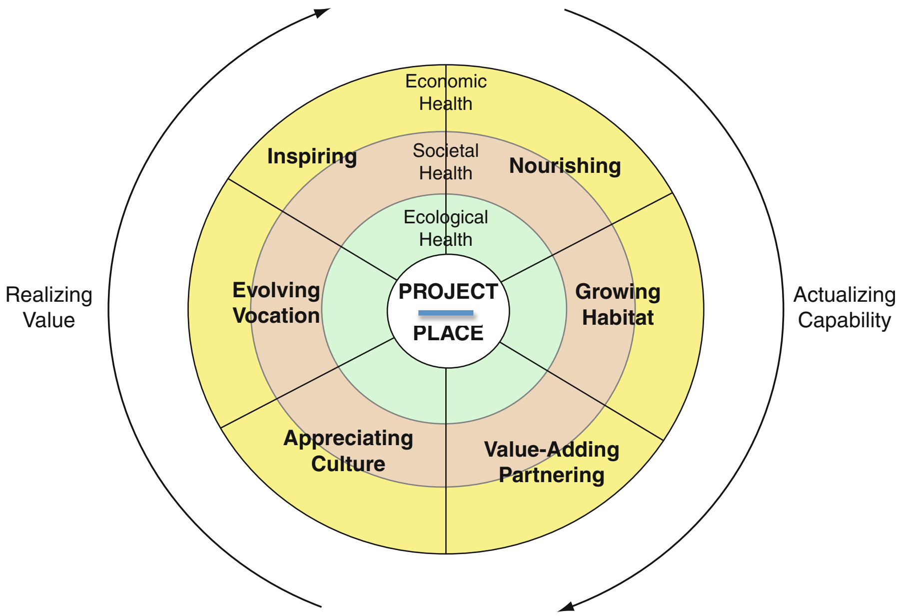
Before farming took place here, these radiating streams and drainage ways served as additional corridors of cover for wildlife moving back and forth between the mountains and the river. When farmers settled the land, they diverted this perennial stream along the highest possible course (in elevation) to irrigate fields that were gridded over a highly productive and robust prairie ecosystem. This action severely simplified and destabilized the ecosystem that once was there. The farming pattern did not preserve the integrity of the pattern that contained it; rather, this larger healthy pattern was obliterated. The ecological function of this alluvial fan, and one of the *core patterns* of the ecosystem in this place, is that of a *"living bridge"* between the mountains to the west and the Teton River.

The pattern of a living nutrient bridge between the mountains and the valley that had been revealed in the assessment indicated that a higher level of potential health can be reestablished in this mountain, alluvial fan, and River system. The development of homes in tight clusters could be used to pay for the restoration of the stream and habitat corridors that originally connected the Teton River and the mountains and provide wildlife corridors as well as many ecosystem services for community residents. To support the reestablishment of wildlife corridors, no fences would be allowed, native grasses would be planted (minimal turf grass), no off-leash dogs to disrupt nesting, and territory establishment by new wildlife.

By integrating the community into the development and management of these systems, they could produce food (through diversified agriculture and wild harvesting), timber, and other products, as well as the development of a diversified economy while insuring the provision of ecosystem services for their community. The human involvement in these patterns and processes is key to the ongoing regeneration and development of potential of the site.

Designing for Harmony with Place *Biomimicry*: The Biomimicry Guild's Life's Principles and their Genius of Place program provide guidance and models for establishing locally attuned strategies for building design through looking at how local species live out universal ecological principles within the conditions of a particular site and its surroundings, and how they have adapted to thrive within it (web link: www.biomimicryguild.com/).

Permaculture principles, which draw both on an understanding of ecology and of how indigenous people engaged with their place provide a lens for developing design strategies for responding to site conditions and



Regenerative Development and Design. Figure 8
Framework showing interrelationship of the 6 essential living processes and how they cross ecological, societal, and economic arenas. Used to set holistic, integrative goals and indicators. © Regenesis Group. Reprinted with permission

opportunities in a way that is mutually beneficial (http://permacultureprinciples.com/; www.tagari.com/).

Two other useful frameworks that can be utilized as a part of the designing for harmony phase include:

A Regeneration-Based Checklist for Design and Construction (SBSE).
Malcolm Wells' Environmental Checklist.
www.sbse.org/resources/docs/wells_checklist_explanation.pdf

Essential Living Processes Framework: This framework was developed by Regenesis for setting overarching project aims to guide the design and construction process. It is based on the six critical processes that enable living systems to support the evolution of life. They include the ability to provide the material structuring that forms the basis for life processes – nourishment, shelter (habitat), and the generation and exchange of resources for growing and evolving more life. Because humans cannot be separated out from any living system, the factors go beyond the material factors – the outer landscape of a place. They also include the "inner landscape" that sources one's spirit and will and drives one to cherish and protect the places one inhabits. They include the ability of a living system to create a sense of identity and foster belonging through its culture, to support meaningful and contributory lives, and to invoke the spirit and inspiration that sustains caring. The framework enables setting aims and goals (and later developing indicators and measuring systems) for how the processes generated by the project support ecological, economic, and social health in each of the six areas. The interrelationship of these processes and how they cross ecological, societal, and economic arenas is graphically represented in Fig. 8:

An example of ecological aims for nourishing:
Capacity of soil, water, and air to nourish life –
Aims:

- Invest water in increasingly higher order life processes through storing and cycling (vs. hoarding) so water becomes the driver for improving soil and air quality.
- Products and processes used in construction and operations are investments in growing the capacity of soil, water, and air to store, transform, and transport nutrients for optimal accessibility and utilization.

Future Directions

While regenerative development and design still occupies a relatively small niche in the larger world of sustainability efforts, interest in regenerative approaches to the built environment is on the rise. Beyond the USA itself, this growing interest has been particularly marked in Australia and New Zealand, including a government-commissioned research report that recommended the latter adopt regenerative development as a national policy [10].

A number of interrelated factors, working as a system, are creating a favorable climate that is likely to continue to feed such interest, among them: more practitioners encountering the limits of green building to address the global crises, shifting market dynamics and public awareness, the growing influence of the ecological perspective and the ecosystem concept, the movement toward integrative design with its reliance on interdisciplinary teams, and the growing recognition of the need for community engagement and participation to support the behavior changes required for enduring sustainability.

In the 1990s, the most discussed issue for aspiring green designers was how to convince clients to incorporate sustainability features. By 2010, the discussions increasingly were about how to meet clients' demands for making their project "the greenest" of their kind. Over the same period, appreciation and understanding of ecological sustainability and the ecosystem perspective as it applies to human settlements and institutions has been significantly reshaping thinking in such fields as public health, education, economic and community development, and urban planning, as well as design of the built environment. Its core concepts, especially the concept of seeing communities as ecosystems in which nature and culture, human and natural designed features are interwoven and interdependent, are driving a move toward increasingly systemic and comprehensive goals. These comprehensive goals are, in turn, defining new standards of sustainability. Projects seeking to be "the greenest" now include social, economic, educational, and esthetic goals as well as goals around energy efficiency and pollution. More comprehensive goals affecting multiple fields are necessarily stimulating more integrative and interdisciplinary approaches. They are also adding the need to build community support and stewardship to the list of essential design issues. The ecological and ecosystem perspectives are providing a common "language" or set of frameworks across those fields that is facilitating integrative and participatory approaches across disciplines and between design teams and the public and in the process, further reinforcing an ecological worldview.

One effect of this system of factors has been the extension of explicitly regenerative approaches across a wider spectrum of fields and the integration of these fields with regenerative development of the built environment as part of regenerative community development. Regenerative development had already begun to shift the old, building-centric definition of the built environment to include the relationships between and among buildings, infrastructure, and natural systems, as well as the culture, economy, and politics of communities. Its concept of place-sourced design is providing a means of engaging the will of a community around aligning human and natural communities around shared purposes. Given its holistic and integrative character, it could be anticipated that these more comprehensive applications will be a continuing trend.

Regenerative Development makes possible a new and critically needed role for developers and developments, the full potential of which is still unfolding. Development projects already exist that, by the way they are built and occupy land, serve as instruments for reversing ecological damage, and as economic forces for constructing sustainable livelihoods. Still other projects offer glimpses of how, through weaving the many stories of Place into a mutually appreciating whole, a Regenerative Development becomes a harmonizing force within communities and among different stakeholders, inspiring new standards of appropriate relationship to Place. It is possible to envision how, by introducing larger systemic vision and potential, development can become a catalyst for the creation of self-evolving bioregional infrastructures and cultures of regeneration.

While this new role is beginning to emerge in small scales and at scattered locations, it is largely unrecognized as being part of a larger evolution. What is needed now is to bring consciousness and intention to its emergence as the new pattern shaping the field of development.

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Resource Repletion, Role of Buildings

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Article Outline

Glossary

Improving the approach to materials and products sometimes requires revising traditional terminology. In the approach described here, usage of certain terms differs from traditional definitions, to account for innovative features of materials and products.

Biobased vs. biodegradable Many biobased products such as, for example, biopolymers are not necessarily safely biodegradable because they contain additives such as heavy metals or are combined with nonbiodegradable materials. As well, petroleum-based products that are not biobased can be biodegradable. So it is important to distinguish these features to develop an effective defined-use pathway for materials. Especially, it is important to evaluate biobased and biodegradable in the context of the intended use of the material, e.g., if it is intended for a biosphere or technosphere pathway. For example, many materials designed for single use before disposal in a biosphere pathway and defined as biodegradable, such as cups, do not biodegrade in the processing time frame used in an industrial composting facility and, as a result, end up being incompletely decomposed and incinerated, or degrade the quality of compost. Because of this, the definition of "biodegradable" includes that the material is shown to degrade completely in an industrial composting facility within a prescribed time frame.

Counter-footprint Calculation showing activities that can be used to counterbalance a negative "environmental footprint." Example, producing renewable energy instead of just consuming energy. Counter-footprinting is still at an early stage and often, for example, does not calculate defined material content, defined-use pathways, or beneficial functions of materials such as, for example, cleaning the air. For example, Coto-Millan et al. [1] list construction materials as resource consumption, but not as a material resource on the counter-footprint side of the equation. The part of land "consumed" for structures is regarded only on the negative side of the footprint equation, rather than as a productive contributor to the ecology. In general, when materials are used for constructing a building, their impacts are frequently still considered only on the negative side of the environmental footprint and no longer considered as beneficial resources. See also "offset."

Cradle to Cradle® An innovation platform to improve the beneficial qualities of products and services in biosphere and technosphere metabolisms as a step beyond the traditional sustainability approach of reducing negative impacts. The term *Cradle to Cradle®* is a registered mark for quality assurance purposes, similar to how the broadly accepted International Standards Organization governs use of its marks and standards. However, the philosophy, principles, and many application tools of the Cradle to Cradle® approach are widely published. The founders of the C2C approach encourage governments, companies, and NGOs to use the

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philosophy and principles. The right to use the Cradle to Cradle Design Protocol® for certification is assigned to an independent nonprofit organization, and certification criteria are also broadly published.

Defined use Materials and products that are designed according to their intended use in biosphere or technosphere metabolisms.

Depletion Loss of nonrenewable resources and destruction of renewable resources.

Ecological footprint Usually a calculation of negative environmental impacts of human activity. Many definitions are used, but an example in relation to the built environment is "Corporate ecological footprint is defined as the environmental impact (in hectares) of any organisation, caused by: (a) the purchase of any kind of product and service clearly reflected in their financial accounts; (b) the sale of products deriving from the primary production of food and other forestry or biotic resources, or in other words when vegetables, fruit and meat enter the market chain for the first time; (c) occupation of space; and (d) generation of waste clearly reflected in their environmental report. Moreover, this impact measured in hectares can be transformed to obtain a result in tons of CO_2 emitted (the carbon footprint)..." [1]. See also Counter-footprint and Offset.

Intelligent materials pooling (IMP) Sharing of defined material streams among partners to achieve economy of scale and accelerate the use of C2C-defined materials.

Materials bank Database-supported pool of defined materials.

Materials security Security of supply for strategically important materials such as rare metals or phosphate.

Nutrient certificates Set of data describing defined characteristics of materials in products that give them value for recovery and reuse. Nutrient Certificates are a marketplace mechanism to encourage product designs, material recovery systems, and chain of possession partnerships that improve the quality, value, and security of supply for materials so they can be reused in continuous loops or closed loops or beneficially returned to biological systems. This is done by adding a new value dimension to materials quality. This new dimension is based on the suitability of materials for recovery and reuse as resources in other products and processes.

Offset Assessment of activities that compensate for negative environmental impacts. As opposed to counter-footprints, offsets are often used to describe remotely located activities, such as growing trees in another location to replace trees lost due to development. However, counter-footprint and offsets can also overlap.

Recycled vs. recyclable Products can be beneficial if they have defined recyclable content regardless if it is recycled or not. Defined recyclable content is an enabler for recycled content. If virgin content is not recyclable then it will pollute recycling streams, so recyclable is just as important as being recycled. Recycled content that is also recyclable at a similar level of quality is the end goal of product design for Nutrient Certificates.

Recycling There are many definitions of recycling, but for these purposes, recycling is defined as recovering and reusing materials at a similar level of quality by defining their content, as compared to "downcycling" where materials are recovered and reused at a lower quality level. For example, the term "recycling" is often applied to materials such as paper, but in reality, paper is almost always downcycled due to shortening of its fibers. Many current definitions of recycled content do not define what is in the material, with the result that it is not possible to recycle the materials at a similar level of quality. The important distinguishing factor is "defined" content, which can be indicated as defined to 100 ppm.

Repletion Replenishing the supply of biosphere and technosphere materials for use in products and processes.

Scarcity Geographically, politically, or commercially limited supply of strategic materials.

Upcycling Improving the existing quality of a material for its next reuse. A material can be defined as upcycled under various conditions:

(1) When its current downcycling is improved so the material is recycled at a similar level of quality instead of lower level. For example, high-grade steel is separated from motors containing copper

contaminants so the steel can be resmelted at the same level instead of downcycled

(2) When a degraded material is repaired for effective reuse, e.g., an additive is added to a plastic to repair its damaged molecular strings so the material can be reused for a high quality purpose

Definition of the Subject

Raw materials scarcity, rising raw materials extraction costs, and biodiversity loss are apparent globally. Recycling of materials is cited as one solution to those problems. However, maintaining the consistent quality of materials is excluded from most traditional sustainability assessments, and current regimes of carbon, emissions, and energy trading are not well designed to account for the quality or value of materials, or the processes for achieving materials recovery and reuse.

The building industry is a large consumer of scarce resources, and because of this, it is regarded as a leading cause of resource depletion. However, at the same time, materials contained in and moving through buildings have been extensively evaluated for their recovery potential [2], and as a result, could be used in a new model where buildings are resource repleters instead of depleters. Materials repletion is a value-based business model that defines new dimensions of quality to generate quantifiable benefits for builders, suppliers, building occupants, operators, and owners. For this model, the inherent conservatism of the industry could work in favor of a new approach due to the emphasis on value, reliability, and documentation. This would introduce a new type of beneficial agenda into the supply chain of the construction, operations, maintenance, decommissioning, and recycling industries.

To support this beneficial paradigm, a framework for resource repletion and security is described where materials are defined according to qualities that enhance their bankable and tradable value. The concept of *Nutrient Certificates* is introduced as a counterpart to emissions certificates to account for the value of defined high-quality material flows. The focus is distinct from mechanisms such as environmental product declarations, material safety data sheets (MSDS), or emissions trading. For this approach, new criteria are introduced for materials and for "recycled content." Financial enabling innovations are described, and early adopters are identified among governments and companies, including participants in Cradle to Cradle® networks.

Introduction

► Our economy will run out of materials before it runs out of energy.

(Michael Braungart 2009)

► China…has now quietly halted some shipments of (rare earth metals) to the United States and Europe… industry and government are joining forces by appealing to the European Commission and the World Trade Organization to intervene…

(*New York Times* October 19, 2010 [3, 4])

The globalized depletion of material resources is well documented quantitatively and qualitatively [5]. Skeptics argue that such claims are exaggerated [6] and that scarcity has a positive side effect of driving innovation. Despite those arguments, scarcity is still disrupting economies. This scarcity is generated more by geopolitical distribution inequity than geological availability. For example, Europe depends on just two countries, China and Morocco, to support most of its agricultural system with the fertilizer phosphate. In 2008, China puts export tariffs on its phosphate supplies, disrupting phosphate pricing [7]. China also has a near-monopoly on producing certain rare metals, not because of geographic distribution but because other countries let their rare metal processing capacities dwindle [8, 9] via outsourcing. The city of Barcelona once had to import water in ships due to a water shortage, resulting in prioritization conflicts with other regions of Spain [10]. As well, Central and Southern Europe suffered when Russia interrupted gas supplies.

In addition to distribution disruptions, the costs of extracting material resources are accelerating as supplies become more remote and difficult to access. Biodiversity losses are accelerating as species habitats are put under greater pressure by expanding incursion for urbanization and resource extraction [11].

Together, those factors pose economic security risks to regions such as Europe, USA, and Japan, along with suppliers such as China who come under pressure to solve shortages by exporting their own limited supplies.

Materials security is taking the stage alongside energy security as an economic and military consideration. This is generating an economic, social, and ecological imperative for materials repletion instead of depletion.

A first step to establishing a materials repletion paradigm is to recognize the unintended consequences of traditional approaches to "sustainability," which pose barriers to repletion. The step after that is to describe solutions for those unintended consequences.

Unintended Consequences of Traditional Sustainability

The Unintended Consequences of Eco-Efficiency

The traditional approach to materials sustainability in buildings is exemplified by the draft topical outline provided to the authors for this article:

- Green sustainable building is the practice of increasing the efficiency with which buildings and their sites use and harvest energy, water, and material, while at the same time reducing impact on the local and global natural environment. [12]

An unintended consequence of this approach has been that greater efficiency often has the opposite effect by accelerating instead of reducing impacts. This is self-evident, for example, with accelerated material and energy throughputs for personal electronic devices. Here, efficiency improvements in the use of materials and energy have been exceptional over past decades. Miniaturization resulted in devices that require only a fraction of the energy and the materials compared to earlier devices to perform the same function, while at the same time adding functional features. However, this resulted in price drops that made the technology accessible to billions of customers, generating exponential increases in materials and energy throughputs due to collective demand [13]. By increasing the efficiency of individual devices, the industry accelerated collective materials and energy throughputs, including flows of materials for products to waste from product disposal.

The same occurred with buildings, as efficiencies have improved and economic activity expands globally, real growth in the collective "ecological footprint" of buildings (see Glossary) has accelerated in developing economies of Eurasia, Africa, the Middle East, and South America, while still expanding in developed economies of Europe, North America, and elsewhere. The results are marginal reductions in the footprints of individual buildings negated by the collective expansion of land use, materials, and energy. In many cases, individual building footprints are increasing as well to house diverse technologies and the lifestyles they suggest. Electronic technologies and networking services in particular are growing rapidly, resulting in increasing demands for space, materials and energy.

This collective expansion of impacts due to economic and technological development is also described in recent studies finding that wealth, not poverty, is the main driver of environmental impacts [14]. As collective wealth improves globally, consumption of energy and resources is accelerating.

Due to the phenomenon of efficiency accelerating throughputs, the "reduction" approach to resources on its own is unlikely to significantly mitigate environmental impacts in buildings or of products that move through them, and instead is likely to accelerate those impacts.

Disregarding Beneficial Footprints

- Minimization vs. Benefits. Green assessment methods focus more on minimizing use of materials and energy instead of focusing on the intended benefits of materials and energy in a system. As a result, the value of some beneficial aspects is underemphasized in green building standards. By contrast, natural processes often maximize their own footprint, and an example of this is the largest living thing on Earth, the giant sequoia. See following sections for example.
- Measurement Criteria. To accurately assess the benefits of some materials, it is important to evaluate factors such as their "defined use" in ecosystems, the active benefits they generate, and the time frame and rate of reuse, as discussed under Section III. Current measurement systems often disregard those.
- Assessing Impacts vs. Calculating Resources. Most green rating systems for buildings do not award many points for designing materials as resources for the future. Instead, those materials are often considered as part of a negative "consumption"

footprint. Until now, this has been justifiable because many building products today are not designed with next use in mind, so they are not considered beneficial resources. But the unintended consequence is that when green rating systems do not encourage the transformation from minimizing impacts to maximizing future resources, they become part of the problem instead of the solution. An example of this can be found with "recycled content."

Unintended Consequences of "Recycled Content"

Part of the approach of green rating systems to materials depletion includes "recycled content" and "reuse of materials." However, those rating systems do not distinguish, for example, materials downcycled from high to low quality from materials with recycled or "virgin" content that is defined, easily separated, and recyclable at a similar level of quality. For example, LEED 2009 for existing buildings does not require "postconsumer recycled content" to be defined or to be recyclable at a similar level of quality [15]. Also BREEAM 2010 standards for real estate specify materials with a "high recycled content" and "reuse of materials," and although these also specify "nontoxic" materials, the standards do not specify defined or recyclable at a similar level of quality [16].

As a result, companies that invest in important quality aspects such as design for materials recovery are sometimes penalized for focusing on those investments. For example, well-defined virgin material for ongoing use would not receive credit, whereas undefined downcycled material would. Nor are actively beneficial functions of materials considered. So, a building containing materials defined to 100 ppm and consisting of surfaces that clean the air would not qualify under many green building evaluation systems because those materials do not contain "recycled" content. The defined content for ongoing use and the functional qualities of materials might be more beneficial for the building than undefined recycled content, but those benefits are underemphasized in Green building scoring systems and regulations.

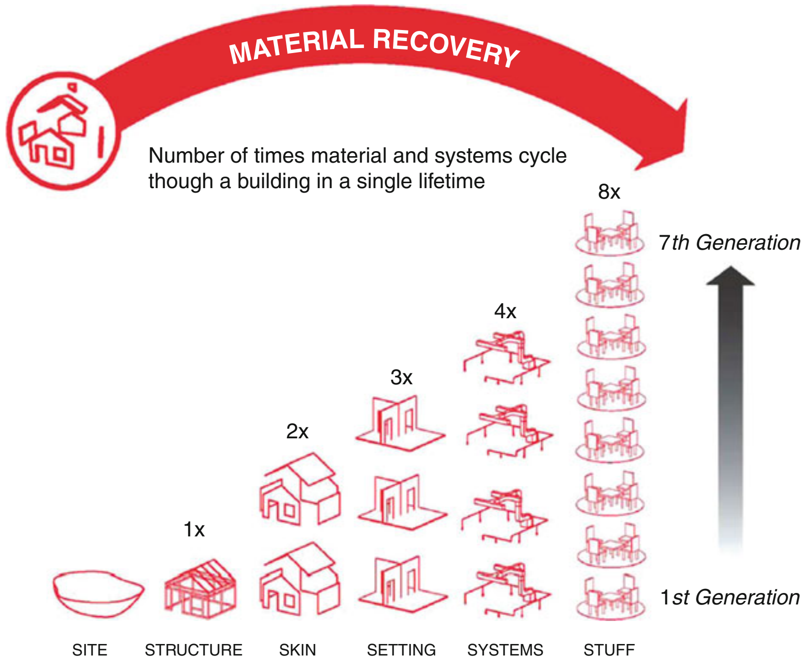
This is especially problematic if contract tendering documents require contractors to maximize the amount of materials recycled or reused from an existing building into new construction or renovation. By mandating maximal on-site reuse or recycling, contracts can inadvertently penalize contractors who use well-defined materials wherein the next intended use as agricultural or industrial resource is known. Tenders can also discourage other innovative off-site reuse or recycling of materials that might be more suitable, including the reuse of those materials unsuitable for human exposure in a building.

> This is not to say recycled content is a bad requirement, but rather that the traditional definition could be improved to reward other properties and promote the use of defined and truly recyclable materials.

Likewise, material safety data sheets (MSDS) for products contain a list of aspects defined as hazardous and how to handle those, but are not designed to show the beneficial qualities or whether a product is sufficiently "defined" to be recycled at a similar level of quality. Nor are MSDS intended to evaluate the suitability of materials content for recycling after their first installation. Indeed, a material might be contaminated with an additive that makes it unsuitable for recycling, but this would not be described in the MSDS. Nor do MSDS keep up with science effectively. They are based on regulatory definitions that usually take many years to recognize hazards in products, long after the hazard has been established through scientific analysis. The effect of this is to increase contingent liabilities for companies because something that might not be listed on an MSDS today might suddenly appear when legislation changes. So MSDS provide no early warning system to prepare companies and owners for new findings.

Consequences of Traditional Assessment Boundaries

Beyond the confines of product selection, very little attention is paid to what happens to the products and materials that flow through buildings. Over the lifetime of a building, flow through might equal or exceed the mass of its construction materials. Often, no score is assigned to the quality of material in office equipment, furniture, and finishes that flows through the



Resource Repletion, Role of Buildings. Figure 1
Number of times materials and systems cycle through a building in a single lifetime. It can be seen here that buildings are effective mechanisms for tracking materials with relatively short turnover periods as well as those with extended turnover periods, and that the shorter-term innovation potential is with products that have shorter generations for optimization (Source: Redrawn from a William Mc Donough & Partners drawing adapted from Brand 1994 [44])

building, including food, paper products, and other biogenic materials, as illustrated in Fig. 1 in a following section.

The emphasis of assessment language on being "less bad" is endemic throughout the literature. For example, the terms "minimize" and "reduce" are used throughout LEED design innovation credit documents [17]. Terms such as "offset" are used to signify compensation for negative impacts, and reference is also made to habitat conservation, but those approaches are rarely used in reference to materials quality. Nor are they intended to transform buildings into net positive generators of biodiversity, energy, or defined materials. Instead they are largely directed at reducing or compensating for the negative impacts of a building.

The effect of this language is that most attention and funding is spent on minimizing the negative impacts of building materials, and less attention is paid to evaluating or improving the benefits of material quality.

> Such examples are not intended to discredit green building ratings as a mechanism, but instead, to show that limiting boundaries and emphasis can skew the focus of investment and limit the capacity to be truly beneficial. When boundaries are too limited, innovation is limited.

Unintended Consequences of Biomass Energy

The value of biological materials in buildings is usually considered in terms of how much wood and other agricultural products are used during construction. However, one of the largest components of biomass use for buildings, and one of the fastest growing in terms of investment, is biomass for energy [18]. It is noteworthy that technology has progressed over the centuries toward increasingly intensive embodied-energy fuel sources, from biomass to coal to oil to uranium, but now seems to be regressing to biomass. The widespread burning of virgin wood and other biomass is now sanctioned as "sustainable" and is given government incentives. However, the impacts of that burning whether in Africa or Europe are quickly becoming apparent in resource depletion. For example, a FAO study estimates that despite uncertainties over data, an approximately 400 million cubic meter shortfall by 2020 can be projected for wood availability in Europe [19]. This forecast was already manifested in 2010 when some biomass incineration facilities had to start limiting operations due to supply shortages. Europe would have to cut down many of its forests and use much of its farmland to meet this shortfall, so instead, it is importing wood from the Americas, Russia, South-East Asia, and Africa to meet demand [20]. Moreover, the fertilizer requirement for growing such large amounts of biomass is usually not considered in forecasting e.g, the capacities of soils to continually produce biomass that is not returned to the soil. The costs and materials flows involved in replacing humus, NPK, and trace elements are often absent from biomass supply chain estimates.

> This is not to say biomass energy is inherently impractical for meeting a minor portion of energy demand, but rather that current strategies are already leading to shortages and have not adequately considered nutrient flows required to meet production requirements. Nor do they consider the unintended consequences for the wood construction, pulp and paper, and furniture manufacturing industries that find themselves adversely affected by subsidized biomass burning [21].

Confusion Over Biobased Materials

Large investments are being directed into biobased materials, but at the same time, there is much confusion in the marketplace over what biobased materials are and under what conditions they are eco-friendly. "Biobased" is often confused with "biodegradable." Biobased materials are often not safely biodegradable due to the additives they contain. Nor are biobased materials necessarily eco-friendly. They can compete with food supplies and lead to topsoil depletion. To solve this, a systematic implementation regime is required that can define conditions under which biobased materials are beneficial along their intended pathway of production, use, and disposal.

Impracticality of "Local Materials" Criteria

In a globalized economy, sustainability criteria that reward local sourcing of materials do not adequately address regional materials imbalances. For example:

- Rare-earth metals required for industry are found in just a few countries.
- "Fair trade" regimes often involve transport of goods long distances to locations where similar resources are impractical to produce, e.g., coffee grown in Africa would require vast greenhouse complexes in Alaska.
- Innovative materials such as, e.g., Nanogels® that improve the performance of buildings are only manufactured in a few locations. Green building assessment systems such as BREEAM give preference to "local materials" [16]. Under those rules, innovative materials could be penalized.

While sourcing local materials, components, and labor can sometimes ensure reduced transportation costs, enhanced employment, and industrial durability in a region, and may source more climatically appropriate materials, those goals need to be modified to recognize where local sourcing is not the most practical alternative.

Deficiencies of Emissions Trading Schemes

Because emissions trading schemes and habitat offset schemes are usually characterized in terms of energy and wildlife, these are usually not referred to in relation to materials quality. However, those schemes are largely materials dependent. For example, fuels are materials. Energy systems in and for buildings are made of materials. Substances that make up habitats are materials. Greenhouse gases are made of chemicals that can be reused. Those examples suggest that emissions trading schemes are as much materials depletion and repletion questions as they are climate change or energy questions.

Emissions trading schemes are inadequately designed to promote conditions necessary for regenerating materials resources. For example, there are few if any emission credits for directly regenerating our primary carbon-sequestering systems, such as topsoil which is the upper 1–2 m of soil required by most plants to grow. Soil organic carbon is the biggest carbon pool of the planet after the oceans and far greater than what is found in the atmosphere [22]. Soil is a forgotten climate solution. Aside from the oceans, top soil is the leading repository of carbon in the biosphere. Much of the productive topsoil globally has been lost in the past century due to industrialized farming, soil compaction, erosion, and urbanization [23]. This loss has been a leading contributor to carbon release into the atmosphere. Conversely, soil conservation is shown to sequester atmospheric carbon [24]. Emissions trading schemes can be used to support soil conservation, which is distinct from soil manufacturing, but they do not account for the nitrogen, phosphorous, potassium (NPK) fertilizer cycle in topsoil, or soil quality degradation from rock phosphate fertilizer that is contaminated with uranium mined with the rock phosphate [25].

Topsoil is often not considered as a significant factor in buildings, but actually, buildings and topsoil have substantial interactions. Buildings usually occupy space where topsoil used to be. Runoff from buildings has substantial impacts on topsoil. Landscaping for buildings makes extensive use of topsoil. Products used in buildings are often made from biomass grown in soil. So it can be said that buildings rely heavily on topsoil. Because of this, converting buildings from materials depleters to materials repleters also involves a basic revision in the approach to soil.

Due to those various factors, emissions trading schemes are ill-equipped to support or quantify materials flows that are essential for the continued development of our industrial society. However, it is not the intention here to describe all the pros and cons of such trading schemes, as these are described elsewhere [26].

Instead, the main purpose here is to point out that those systems often do not recognize the role of materials. They often do not quantify the contribution of materials to carbon sequestration, biodiversity, nutrient recycling, and other beneficial aspects. They do not distinguish between high quality and low quality recycling.

Materials Repletion for an Abundant Healthy Footprint

How might it be possible to solve the unintended consequences of traditional sustainability approaches? Practical lessons can be taken from natural systems.

Big Footprints Can Be Beneficial

One example of a big, healthy footprint is the largest living thing on Earth, the giant sequoia [27]. Like many buildings, it reaches heights of more than 90 m, weighs thousands of tons, and uses thousands of liters of water and large amounts of energy daily. As the fastest growing tree in the world, it consumes large amounts of energy to pump nutrients and relies on the massive transport of water from hundreds of kilometers away to provide the marine layer that feeds the forest canopy. Its outer skin is far from minimal; it is thicker than the outer skin of many buildings and can be more than a meter thick. Its root system extends farther underground and laterally than the foundations of many buildings. The total throughput of energy and materials of a forest containing giant sequoia and similar giant tree species can rival that of small human settlements. In total, the giant sequoia has a giant footprint.

The sequoia also depends on destructive processes. It depends for its early existence on fires that pollute the environment and kill other trees, clearing the forest floor so sequoia species can compete and get established. To protect itself, it uses the toxic material tannin which can be harmful to insects and other wildlife. At the same time though, the sequoia has a maximal beneficial footprint, which can be described as an "offset" or "counter-footprint" [28] (see Glossary) that maximizes the positive use and reuse of resources. It provides a habitat for hundreds of species, generates oxygen, beneficially uses CO_2, filters the air, is an exceptionally long-term carbon sink, and sheds biomass that is converted into soil.

Its cellular capacities allow it to use large amounts of water while returning it to the environment in a state beneficial for other biosystems. Its immune system resists disease, letting it live more than 3,000 years. The species is so genetically successful, it has outlived the dinosaurs.

Maximizing Benefits is More than Just Semantics

While the distinction between "maximizing benefits" and "minimizing impacts" might seem like semantics, it extends far beyond terminology. Natural design principles are increasingly recognized by architects and designers and applied to building and product designs through techniques such as biomimicry and calculation of offsets or counter-footprints. When innovation is directed at maximizing benefits instead of minimizing damage, different outcomes occur. For example, instead of minimizing the amounts of rare metals in devices to a level where it might not be economic to recover them, the designer focuses on design for disassembly to recover those rare metals so they can be used again. This approach might in some cases increase the amounts of rare metals used, but also enables their recovery. In this way the materials can be used as resources for other industrial processes.

This different approach can be seen in the Cradle to Cradle® approach to resource reutilization.

Cradle to Cradle® for Achieving Resource Repletion and Beneficial Footprints

The Cradle to Cradle® (C2C) [29] approach emphasizes those beneficial factors. The "Cradle to Cradle" Design Protocol® has taken an approach that generates benefits for stakeholders by going beyond the "cradle to grave" and beyond traditional interpretations of "environment."

Cradle to Cradle® is a paradigm-changing, quality-enhancing innovation platform developed in the 1990s by Michael Braungart, William McDonough, and others based on research at the Environmental Protection Encouragement Agency [30] in Hamburg Germany, for designing beneficial economic, social, and environmental features into products, processes, and systems. Cradle to Cradle® is primarily an entrepreneurial and innovation approach that starts by determining the intended benefits of a product or service instead of focusing on minimizing negative environmental impacts.

C2C philosophy, principles, and many of its application tools are broadly published, and the philosophy and principles are available for anybody to use with attribution.

The C2C Design Protocol described here, as well as the *Cradle to Cradle® Criteria for the Built Environment* are further described in other publications and are only partially excerpted here [31].

To enhance quality and add value for stakeholders, C2C promotes innovation partnerships along the entire chain of a product, including manufacturing, distribution, use, disassembly, recovery, and reuse.

By characterizing hundreds of products and thousands of materials for their human and environmental health attributes, as well as defining systems to safely and fully cycle materials into new products, C2C has already provided a practical yet inspirational scientific and business model for improving quality.

This innovation and value model makes C2C potentially attractive to planners, builders, and manufacturers for integration into products, processes, buildings, materials recovery systems, and purchasing.

Extensive books, cover stories, and documentary films have been published and broadcasted about C2C since the 1990s. The book *Cradle to Cradle* [32] is well known and translated into at least a dozen languages. However, many planners are not yet familiar with how to integrate into the built environment C2C features such as beneficial materials. There is a tendency when encountering well-known phrases such as "safe materials" and "species diversity," to respond with "yes we do that already." But most buildings and area plans do not incorporate defined-use pathways for materials. Methods are still not well established for designing sites so they contain "defined" materials, or are species-positive.

Various guidelines for C2C in the built environment were integral to published declarations such as the Hannover principles [33] and more recently in The Netherlands, the Almere principles [34].

Those extensive documents are only effective if they can be translated into measurable results. The first step is to understand the overall C2C framework, then study and implement the three defining Cradle to Cradle® principles encompassed in that framework.

C2C Framework
Cradle to Cradle® can be divided into these categories that together make up the C2C Framework;
(1) Philosophy e.g., a quality-based innovation platform for benefitting the economy, ecology and social equity.
(2) Principles that are translated into measurable criteria.
(3) Application tools.

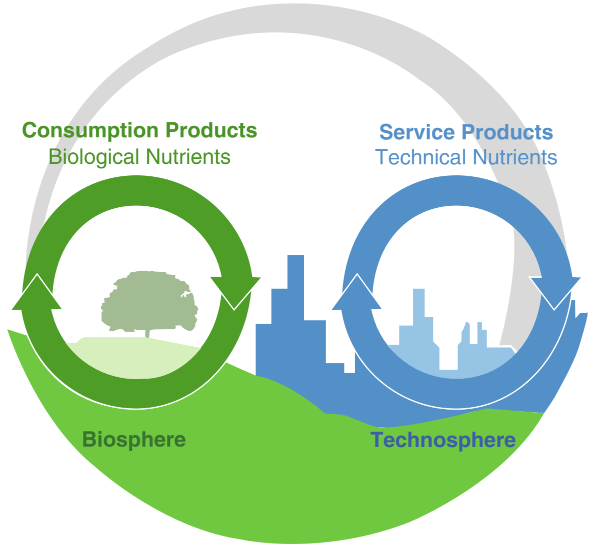
C2C Principles
Waste = Food. Everything is a Nutrient for Something Else.
Use Current Solar Income. Energy that can be Renewed as it is Used.
Celebrate Diversity. Species, Cultural, and Innovation Diversity.

These principles define and support two types of metabolism for every product and process; biosphere metabolisms for products designed to support biological processes, and technosphere metabolisms for products designed to provide a technical service and whose materials are continuously recycled. See Fig. 2.

Using the C2C principles as a basis, a Cradle to Cradle® building can be defined this way:

A Cradle to Cradle® building contains defined elements that add value and celebrate innovation and enjoyment by measurably enhancing the quality of materials, biodiversity, air, and water, using current solar income, being deconstructable and recyclable, and performing diverse practical and life-enhancing functions for its stakeholders.

The definition also applies to materials and products such as furnishings, cleaning materials, and office equipment that move through buildings because, often, things that move through buildings have equal or greater impacts on the economy, environment, and users than the structures themselves. This "moveables" factor is often underemphasized in various "green" guidelines for buildings, but it is a central feature of the Cradle to Cradle® approach.



Resource Repletion, Role of Buildings. Figure 2
Cradle to Cradle® metabolisms and product types

Ten Criteria for Applying and Quantifying C2C Principles in Buildings

Broad principles are a prerequisite for eco-effectiveness. However, measurable criteria are also important for practical implementation. The following ten criteria for applying C2C principles have been organized to facilitate implementation.

Through these criteria, materials in buildings can be defined to constitute a new value chain (1) themselves, (2) through the services they provide in a building, such as cleaning air. For example, defined materials often have a greater recovery value than undefined ones due to their enhanced qualities, but it can also result in cleaner air and water flowing through a building. The quality of air, water, biological nutrients, and biodiversity each constitute value streams that make buildings beneficial contributors. Integrating those aspects also enhances the overall value of a building because the whole is often greater than the sum of its parts. For example, a building whose materials clean the air and water reduces the costs of conventional purification systems.

The ten criteria constitute a guide for achieving those value streams.

State Your Intentions Design is the first signal of human intention. To achieve truly eco-effective solution sets, it is important to design so that; every material can be a nutrient for the next design, every element is generated within our solar income, and the design embraces human- and bio-diversity.

Examples of those design intentions: Do you want the building to contribute air and water that are cleaner than when they were taken from the outdoor environment? Do you want the building to be deconstructable? Do you want to demonstrate that the ingredients in building materials are defined and safe?

Define Materials and Their Intended Use Pathways

(a) Use materials whose quality and contents are measurably defined in technical or biological pathways from manufacturing through use and recovery.
(b) Use materials whose impacts are measurably beneficial for human health and the environment.

For example, a defined product would be a chair whose component parts come from known renewable or recycled materials and energy sources, whose composition is known to 100 parts per million, whose materials are safe for contact with human skin and lungs and can be disassembled into materials that each can be recycled for use in other products or decomposed as beneficial nutrients for biological systems. A "beneficial" ingredient would be an ingredient added to coatings that allows them to actively clean the air.

Integrate Biological Nutrients Measurably recycle biological nutrients and water by integrating biomass production into buildings, landscaping, and spatial plans to generate more biomass, soil, and clean water than before development of the site.

For example, biological nutrients from gray water, biodigestion, and interior and exterior landscaping can be recaptured. Air-cleaning vegetative walls can be designed to metabolize pollutants, and "green roofs" can be designed to retain moisture, capture CO_2, metabolize particulates, and provide oxygen. "Topsoil manufacturing" can be integrated into projects to use biodigestion and composting to produce humus and capture CO_2.

Enhance Air and Climate Quality

(a) Measurably make air quality healthier for biological metabolisms than before it enters a building and provide a comfortable climate for occupants.
(b) Measurably contribute to enhancing outdoor climate by contributing air that is healthier for biosphere metabolisms than before it enters a building and using climate change gases as resources through carbon management.

For example, (a) Air quality can be enhanced by integrating C2C materials across products such as exposed window frames, floors, wall materials, HVAC systems, wall and floor coverings, indoor plants and green walls, furnishings, office equipment, and mold inhibitors. (b) Active carbon management is achieved with vegetation and renewable energy. Climate change gases such as methane and CO_2 are resources that can be used to produce biomass, to be further discussed in later sections.

Enhance Water Quality Measurably improve water quality so the water is healthier for biological metabolisms than before it entered the building.

For example, water quality improvement can be achieved by integrating water recycling systems with nutrient recycling, rainfall capture and storage, indoor plants, and green walls.

Integrate Renewable Energy Integrate renewable energy (current solar, wind, and gravitational income) into buildings and area plans so that the building and site generate more energy than they use. Use exergy as a way to guide energy effectiveness.

For example, integrate "threshold" energy efficiency used in high-efficiency LED lighting with direct current from photovoltaic cells, daylight, ventilation, solar heating, and cooling as renewable energy sources.

Actively Support Biodiversity Integrate measurable species diversity so the area supports more diversity than before development.

For example, species diversity applies to plants, animals, and insects and is quantified by counting numbers and varieties supported by a building. The concept of "natural" or "native" species has to be evaluated in each case because in many regions, the natural environment has been transformed by humans, and returning it to an earlier "natural" state might be impractical.

Support Diversity with Innovation Pursue diversity innovations by focusing on special beneficial features of a building and integrating innovative components that are beneficial for the well-being of occupants and the environment.

For example, diversity gains can be quantified by the variety and prevalence of materials designed as nutrients in a building, the percentage of energy used that is truly renewable, and the amount of beneficial air, water, topsoil, and biodiversity contributed to the outside environment. "Buildings like trees" is a guiding C2C innovative approach. Some innovation can be achieved through biomimicry, e.g., coatings that metabolize pollutants, while others require a level of systems integration that rival the giant sequoia.

Add Value and Enhance Quality for Stakeholders In addition to generating value for the general environment and population, describe what the C2C features of a building do practically for the building owners, operators, and occupants.

For example, cleaner indoor air enhances productivity; recycling water reduces water fees; building integrated photovoltaics can be less expensive than other claddings while providing energy security in regions with irregular power supply; design for disassembly of HVAC systems supports inexpensive replacement during the life of the building; natural lighting cuts energy costs and can enhance human health.

Enhance quality of life for diverse stakeholders Enhance quality of life by designing C2C materials and integrated systems to support sociocultural richness.

For example, innovations can meet C2C principles and make areas safe for children, enhance accessibility, and provide ready access to outdoors and fresh air.

Application Tools for Implementing Beneficial Resource Repletion

Context for C2C Application Tools

C2C principles are primarily qualitative. The criteria related to those principles described earlier are designed to allow quantification of those qualities in buildings.

To implement the criteria and to solve many of the unintended consequences associated with conventional green building criteria, a number of application tools have been developed. These are described more completely in the publication *Cradle to Cradle® Criteria for the Built Environment* [31].

Those application tools are guided closely by C2C principles and criteria. This link distinguishes their use in C2C from how they might be used under conventional sustainability approaches.

For example, C2C approaches CO_2 and energy as *materials opportunities* rather than problems to be "capped and traded" or "captured and stored." Instead of focusing on cap and trade or carbon capture and storage (CCS), C2C application tools would focus on carbon capture and reuse (CCR).

A brief explanation of the C2C approach to energy and CO_2 is an appropriate example, to demonstrate how C2C application tools are applied differently from conventional sustainability approaches;

Cradle to Cradle® (C2C) energy is energy that is generated and applied effectively, using current solar or gravitational income, and material media that are defined as biological or technical nutrients. The definition is qualified and quantified by the following criteria together:

- *Energy sources.* Use current solar or gravitational income, or other defined C2C sources. Primary examples of current solar income use, conversion, and storage include natural light, solar thermal, photovoltaic, photochemical, wave and wind energy, thermal mass storage, and heat exchange. Secondary solar uses include, currently renewable biomass-derived energy from composting, biodigestion, thermolysis, hydrothermolysis, pyrolosis, gasification, and fuel cells. Gravitational income examples, kinetic energy from inertia or weight, e.g., descending waterways. Each of those energy sources is also evaluated under C2C according to the defined use of the material media.
- *Material media.* For generating, converting, and using energy, use materials that contain defined biological or technical nutrients at each stage, converted to energy in the final stage of the material cascade.

- *Energy effectiveness*. Generate and use energy in definably effective ways, using exergy as a way of measuring effectiveness.

From the C2C perspective, carbon dioxide and related gases are a resource. Surprisingly, many methods used to calculate "carbon footprint" of buildings do not include the beneficial use of carbon by, for example, vegetation. Although some carbon footprint methods are beginning to include "counter-footprint" calculations, the concept that buildings themselves could be beneficial users of carbon has not made its way into methodologies.

Primary Application Tools

Because materials and nutrients are the basis for energy generation as well as product manufacturing, the following sections describe three material-related application tools for achieving beneficial resource repletion in buildings including the products and energy devices that are used in buildings:

- Redefining recycling to include defined content and intended use.
- Introducing Nutrient Certificates to quantify the contents and benefits of materials.
- Quantifying and applying economic benefits from those improvements.

Redefining Recycling

The definition of "recycled content" could be improved by including these factors that describe the quality of a product:

Content

What is in the recycled content? For example, are all contents known, especially additives that give materials such as paper, plastic, and metals added functional qualities?

- The material description distinguishes "recycled" from "recyclable" content and "biobased" from "biodegradable" content (see Glossary).
- In the case of recyclable content, the material has infrastructures in place for recovering content.
- For biodegradable content, the material can decompose in available biodegradation facilities. For example, many biodegradable materials do not decompose fast enough in industrial composting facilities and are incinerated. To solve this, the material is defined for industrial composting.

Intended Use

What the material is intended to do and the pathway it is defined for. Intended use is described later in Cradle to Cradle® biosphere and technosphere metabolisms. For example:

- The material is used once then discarded into biological pathways, or is used repeatedly in technological pathways.
- The material can contain toxic materials that perform a function but only if they are safely locked into the material and can be recovered safely for reuse.
- The material performs a beneficial function such as cleaning the air or generating renewable energy.

Material Integrity

- The material can be recycled at a similar level of quality as distinguished from downcycled into lower quality products. If the quality cannot be maintained, e.g., with paper, can the material be downcycled in a controlled "cascade" so its uses are maximized? See *Nutrient Certificates* and *Material Cascades*, as well as Glossary for clarifications on recycling terminology.
- The materials are assembled into the product in such a way that their integrity can be recovered when the product is disassembled.
- If the material is made from recyclable virgin content, then it has a designated pathway for recycling at a similar level of quality.

Distinguishing between Renewable and Recoverable

Sometimes recycling information includes a statement that the material comes from "renewable" resources. However, it is more important whether and how the materials can be recovered and reused as nutrients. This avoids the "renewability" designation being undermined by increasing demand vs. supply of a given material. For example, some natural fibers that only grow in certain regions might be renewable the first year then unsustainable the next when billions of people use them in their products. Wood is renewable until governments subsidize burning it for energy, at which point, it becomes rapidly unsustainable, as occurred in Europe recently. By contrast, "nonrenewable" elements such as silver and gold can satisfy the requirements of billions of users if they are recovered and recycled effectively.

Introducing Nutrient Certificates

The concept of Nutrient Certificates as a counterpart to emissions, energy, and carbon trading was first proposed by Katja Hansen as part of her investigations as senior researcher at The Cradle to Cradle Chair, Erasmus University and is further defined here.

> *Definition*. Nutrient Certificates are sets of data describing defined characteristics of materials in products that give them value for recovery and reuse. The certificates are a marketplace mechanism to encourage product designs, material recovery systems, and chain of possession partnerships that improve the quality, value, and security of supply for materials so they can be reused in continuous loops or closed loops or beneficially returned to biological systems. This is done by adding a new value dimension to materials quality. This new dimension is based on the suitability of materials for recovery and reuse as resources in other products and processes.

Nutrient Certificates have a focus distinct from, for example, Environmental Product Declarations (EPD) [35], whose main aim is to catalog the environmental impacts of a product. EPDs are often based on Life Cycle Assessment (LCA) and as a result, face the boundary and scoping uncertainties as well as methodological variations inherent to LCA methods since their inception. Factors such as embodied-energy, transport distances, and "consumption" of resources play a primary role in EPDs. By comparison, Nutrient Certificates focus on describing what is in the product, especially its suitability for reuse in continuous loops or cascade chains and materials pooling.

Nutrient Certificates are also distinct from, but related to, recyclability indexes [36]. However, those indexes focus more on volumes and weights instead of detailed contents. For example, factors such as coatings and additives are often not considered in recycling indexes, and interpretations of "thermal recycling" differ from the Cradle to Cradle® interpretation.

Why the Term "Nutrient Certificate"?

The term "Nutrient Certificate" is used here to signify the fundamental importance of materials as nutrients for other processes. Instead of ending as unusable undefined waste and poor or unusable nutrients as many materials end today, materials would be defined for continuous reuse as nutrients for other processes.

In this case, the term "nutrient" extends beyond the conventional definition applied to a biological nutrient and includes for example rare metals that are "nutrients" for electronics products.

The term "resource certificate" or "materials certificate" could just as easily be applied, but those terms do not recognize the role of resources and materials as nutrients for continuous processes.

Who Could Use Nutrient Certificates?

Various users will benefit from Nutrient Certificates, for example:

- Chemical manufacturers who want to gain access to new markets based on the suitability of their products for use in recyclable materials.
- Materials manufacturers.
- Complex products manufacturers.
- Designers who want to add value to the products they are designing.
- Retailers who want to include recyclability and materials recovery in their purchasing criteria for products they buy.
- Governments who want to provide the marketplace with certainty about how to define materials recycled content and recyclability.
- Recyclers who have to know what is in a product and how it comes apart.
- Builders, building owners, and managers aspiring to go beyond the confines of traditional sustainability.

Intended Applications of Nutrient Certificates

Enhance Quality, Value, and Security in the Chain of Possession

- Value Chain Enhancement.
  Nutrient Certificates would enhance and reinforce the value chain among producers, users, and

reprocessors of materials. Those materials used in buildings already have a commercial value when they are sold to contractors and installed in buildings. They also have a residual value as "waste" or used products when they are removed from buildings. Nutrient Certificates provide a mechanism to convert that "waste" into a more defined marketable resource whose residual value is enhanced compared to what it might be today. By so doing, Nutrient Certificates also eliminate the cost of "waste" disposal because there is no waste anymore and instead only resources. For further descriptions of value refer to subsection *Quantifying Economic Value*.

- Authentication.
  Nutrient Certificates when combined with "chain of possession" authentication can protect businesses from industrial counterfeiting, adulteration, and diversion, which cost industry large financial losses annually. In this way, the certificates pay for themselves quickly.
- Security of Supply.
  The continuing supply volatility supply crisis for rare-earth metals suggests that security of supply will be increasingly important to companies. Nutrient Certificates provide a basis for reliable material recovery and pooling in defined pathways that guarantee supplies for manufacturers.
- Transition Mechanism.
  The transformation from low-quality waste to high-quality resources will not occur immediately due to the time frame required for industry to adapt to this new paradigm. Nutrient Certificates can support this transition by identifying materials in a product that can be easily extracted as resources, compared to other portions that might have to be disposed of conventionally. This approach can be described as a "roadmap to improvement" where the percentage of reusable material in a product increases over time. This roadmap can be used along the whole pathway of a material by chemicals manufacturers to improve the recyclability of a virgin material and by manufacturers of complex products to make sure the recycled materials contained in those products are themselves recyclable.
- Value Partnerships.
  A value chain for Nutrient Certificates could be established in a partnership between "waste management" companies, who are already transforming their role into that of "materials managers," and product manufacturers who have a direct relationship with materials suppliers. It is in the financial interests of materials managers to work with product manufacturers to upgrade the recoverability of materials because this improves the value of the materials they reprocess and trade. As well, materials managers have expertise that product manufacturers do not; they know what is required to take apart a product so its contents can be recovered, and they work daily in the materials marketplace with logistics and brokering. It is in the interests of product manufacturers to collaborate with materials managers to redesign products because in this way manufacturers know the chain of possession and in many cases offer greater opportunities to retrieve their materials at a higher level of quality and lower cost through greater ease of disassembly and recovery. Some examples of these are already occurring in the marketplace, for example, with glass, metals, and plastics.

Improve Quality Assurance and Risk Management Standards A quality assurance standard lets companies participate in materials pooling while assuring customers of materials quality. Companies increasingly rely on pools of recycled materials for raw materials, but undefined recycled materials carry inherent risks that limit companies' participation in pooling. In addition, toxic product scandals arising from undefined "virgin" materials have demonstrated that quality assurance is required to manage liability risk. Nutrient Certificates can enhance the quality assurance system by defining conditions for intelligent materials pooling or smart pools. This carefully defined type of materials pooling is known as "intelligent" or "smart," because it is based on information networks that let companies participate in the same way they are beginning to participate in smart energy grids, where multiple input and output points are managed with sophisticated information technologies. Nutrient Certificates could also play a supporting role in other quality assurance systems that require transparency. Cradle to Cradle Certification®, Green building standards, and REACH are examples.

Improve Resource Tracking Between Regions Nutrient Certificates could allow for resources to be tracked as they move between regions, for example, the tracking of phosphate in animal feed flowing from South America to Europe, or rare metals in computer parts flowing from China to assemblers in Japan to customers in Africa. Tracking could serve as a basis for nutrient banking and trading to measure nutrient surpluses and deficits, incentives to restore topsoil used for agricultural production, and mechanisms to compare carbon storage and reuse with carbon depletion.

Nutrient Certificates could provide a basis for a globalized system for more accurately determining available stocks especially of rare materials. A globalized database of Nutrient Certificates would be one way to achieve this. However, such a database is not a prerequisite for starting with Nutrient Certificates. In worst case scenarios, inability to reach accurate estimates of the global circulation of some materials would not discredit the Nutrient Certificate scheme, because unlike emissions mechanisms these are not issued by governments on the basis of estimates, but instead, are issued based on defined materials. In that context, the main shorter-term benefits of Nutrient Certificates are to improve value and reliability in the chain of possession.

Examples of the Contents of Certificates

Many of the parameters prescribed here for Nutrient Certificates are not new, although some, such as *Preferred Ingredients,* were developed as part of Cradle to Cradle® application tools. The critical value of Nutrient Certificates is to provide a way of quantifying and valuing the nutrients each material or product contains. In the following sections, an emerging list of material attributes important for Nutrient Certificates are discussed to stimulate further development.

Material Composition

- *Recycled and/or recyclable content* and the chain by which the material can support recycling or reuse at a high level of quality. This includes a description of *recoverable content,* i.e., what portions are recoverable in a defined recovery pathway and accompanied by disassembly or recovery instructions. In the case of complex products, the disassembly instructions are the more important feature, whereas in the case of component materials the recovery instructions are most important. For example, depolymerizing and repolymerizing of plastics.
- *Defined ingredients* in the material. Aspects such as:
  - Physical properties
  - Element composition
  - Beneficial and harmful off-gassing, leaching, or wearing
  - Elution
  - Stable components
  - Contaminants
  - Thermal degradation products
  - Aging of products where they are transformed over their use period
- *Preferred Ingredients.* Has the material been assessed to determine if it contains preferred safe ingredients? This is a fundamentally different approach than only declaring hazardous ingredients or being “free of” hazardous ingredients.
- Defined Nutrient Classes
  - *Material Classes.* Products are comprised of various classes of biosphere and technosphere nutrients; from basic elements such as copper and silver, to basic materials such as glass and paper, and to the hundreds of thousands of additives that give those materials their functional qualities. Those classes can be defined as follows, but it is emphasized that these provisional definitions are primarily for the purpose of establishing the basis for further definitions rather than core to the Nutrient Certificate quantification or valuation methods. For example, defining a substance as a “chemical” or “compound” will not alter its intrinsic value for Nutrient Certificates.
  - *Base Elements.* Base elements in the periodic table, e.g., copper.
  - *Chemicals.* Basic chemicals used in the manufacture of more sophisticated compounds and materials.
  - *Complex compounds.* Complex combinations, e.g., glucose, of basic chemicals.
  - *Basic Materials.* A basic material can contain multiple elements and compounds, but in this definition, it is normally limited to commodity materials that are broadly used in manufacturing, e.g., plastic, wood, biomass, glass, and cotton, which form components of more complex products.

- *Additives.* Additives are referred to here as chemicals that are added to basic materials to give them functional qualities, e.g., fire retardants in plastics. This can also be applied in the case of, for example, coatings.
- *Products, Complex Products.* This is often a confusing category because a product for one industry is often a chemical or material for another. For example, the chemical industry produces base chemicals as products that are then used in other more sophisticated materials and products. However, for these purposes here, a "product" is defined as something that contains multiple complex chemicals or materials, e.g., specialty concrete, carpet, and furniture. A "complex product" would be a product containing hundreds or thousands of materials, e.g., a computer or vehicle.
- *Grade of Material.* Many national and international grading systems already exist to establish material grades at national and international levels for substances ranging from steel and plastics to topsoil. Those systems can be incorporated into certificates if they provide added valuable information. Nutrient Certificates do not have to reinvent quality standards if they are already available.
- *Biobased, Biodegradable, or Both.* A description of whether the whole material including additives is biobased, and if the material and additives together can be safely biodegraded according to their defined pathways or are to be kept in technical cycles.

Material Functions

Actively Beneficial Functions If a material actively performs an enhancing function such as metabolizing pollutants as some synthetic coatings and natural plants do, or producing electric current via conversion of photovoltaic or kinetic energy. It is important to include such features in a Nutrient Certificate to determine if recycling can maintain such properties.

Material-Defined Pathways

- *Material Pools.* Description of the type of material pools where the material can be used after it is recovered at end of use, and the defined material pools the materials is sourced from, if any.
- *Preferred Defined Use.* "Defined use" establishes if the use of the material in a technological or biological cycle has been defined, and if a preferred pathway in that cycle has been identified. This includes the *Cascade Function.* See the later description of cascades.
- *Chain of Possession.* If the materials come from identifiable sources such as a pool of recycled materials, and how far back along the chain of possession they can be traced.
- *Roadmap to Improvement.* Description of roadmap to improving the product or material over time, if any.
- *Authentication.* If the declaration is authenticated by an outside auditor.

Proprietary Information Although proprietary formulas are sometimes seen as a barrier to transparency, mechanisms still exist for validation, for example, a statement that an independent agency has verified the formulas, and a source where the ingredient information can be obtained. Also, in the case of broadly used materials such as grades of plastics, glass, and steel, there are few if any proprietary barriers for larger volumes.

Industry Labeling Compared to Retail Labeling Nutrient Certificates described here are designed for use by industry and government rather than as consumer product labeling. In the future, certain aspects might enhance product labeling for retail customers, but this is not the intention of Nutrient Certificates.

Certificate Categories There are two distinct categories for Nutrient Certificates, differentiating the biosphere and technosphere metabolisms of materials:

Biosphere Nutrient Certificates Because topsoil and biomass are among the leading terrestrial surface repositories for carbon and have direct interface with atmospheric carbon in a cycle that is essential for agriculture, livestock, and forestry, Biosphere Nutrient Certificates (BNC) could provide a quantifiable and beneficial basis for tracking and trading carbon and other important nutrients. BNC would be applied in cases where materials are intended to be returned to the biosphere during or after use. BNC would apply to products derived from agro-industry and forestry sources, or resulting from post-use bio-recovery processes such as biodegradation, biogas generation, topsoil manufacturing, recycled phosphate, and ash recovered from burning of biomass, digestate, or compost.

For example, biosphere Nutrient Certificates could be issued for:

- Food and agro-industry biogenic byproducts
- Digestate from biodigesters
- Manure
- Swill and food from restaurants, households, and other sources
- Fuels
- Paper and paper sludge
- Forestry products
- Biodegradable polymers
- Landscape maintenance clippings
- Ash from biomass incineration
- Sludge from sewage, subject to legislative restrictions
- Phosphate extracted from nutrient streams

Technosphere Nutrient Certificates Technosphere Nutrient Certificates (TNC) provide a quantifiable basis for recovering materials in technical systems, where materials are designed for being used in continuous loops at a similar level of quality.

Technosphere Nutrient Certificates (TNC) could be issued for bulk and commonly used materials such as plastics, steel, aluminum, concrete, and glass, including defined "virgin" as well as "recycled" content, or for more rare materials. For example, TNC could be issued for:

- Base metals, e.g., copper, zinc, silver and rare metals, e.g., gallium
- Defined grades of alloys such as steel
- Defined grades of plastics such as PP, PET
- High quality reusable additives for plastics and metals
- Chemical compounds designed for recovery and reuse

Integrated Nutrient Certificates A complex product containing biosphere and technosphere materials could be accompanied by an integrated certificate describing how biosphere and technosphere components can be separated to become material resources.

Modeling Nutrient Calculations It is not the intention here to describe a detailed model for nutrient calculations. This requires further research into the capacity to quantify each type of nutrient in each type of material. However, as a rule, it is far easier to calculate the actual carbon or nitrogen, phosphorous, potassium, or rare metal content of materials than it is to estimate the "implied" carbon value of many processes, as is the practice with emissions trading today.

Some precedents exist in the C2C methodology for assigning value to nutrients. For example, the textiles company Backhausen in cooperation with Trevira and EPEA has a "Returnity®" certificate [37] that accompanies its products and gives customers a guarantee of 100% recyclability as well as a discount on future purchases if they bring back the product to the manufacturer. The term "Returnity®" embodies the intentions of Nutrient Certificates, returning for eternity.

As well, under C2C certification, a system of "nutrient reutilization scoring" was established as part of a rating system for products [38]. That system, based on an earlier system developed by Braungart et al. and known as the *Intelligent Product System (IPS)* takes into account factors such as Defined Appropriate Cycle, e.g., as technical or biological resources, a documented recovery plan, and "actively closing the loop."

However, the IPS system and C2C certification system are not designed to provide defined information to users and recyclers about features such as material pooling or methods for recovery of nutrients such as phosphate, *in a format that can be attached to materials and tracked along the chain of possession.* Nor are they designed to provide a basis for evaluating the financial recovery value of nutrients in materials.

So, a different type of valuation, authentication, and labeling is required and is further described in the following sections.

Future Directions. Applying and Quantifying Economic Value

Material Cascades In the early sections of this chapter, the unintended economic and nutrient consequences of biomass burning for energy were described.

One way to avoid such misguided approaches is to establish "cascades" of material use and reuse.

Cascades can solve various challenges. (1) With many products such as wood or paper, it is not possible to recycle materials at the same level of quality due to deterioration of components during use and recycling. For example, with paper, fibers are damaged and shortened in each reuse until eventually they become unusable. (2) Biomass for paper takes a long time to grow, so if the paper is only used once, then it is incinerated or composted or downgraded quickly, e.g., toilet paper, then the use period quickly exceeds the growth period required for replacement. (3) Immediate incineration of biomass without using it first in products, or after only one use in a product, releases carbon far more quickly than if the materials is reused in products repeatedly.

In material cascades, the goal is to extend the use of the material for as long as practicable instead of using the product once and then burning or composting it [39]. In a cascade, a material can enter technical loops for multiple uses, then return to biological systems as a nutrient or be incinerated with the ash recovered as a nutrient. Alternatively, if a material such as paper or wood cannot be kept in similar quality technical loops, then its downcycling can be extended in a controlled way by recovering high-quality fibers for use in products for as long as possible (see Fig. 3). This type of controlled downcycling is not to be confused with present downcycling where undefined materials are downcycled with minimal knowledge of their content or pathways.

There are quantifiable economic benefits to material cascades. J. Jokinen calculates that when total employment creation is analyzed, the ratio of reusing wood for pulp and paper industry (PPI) products instead of immediately burning it for energy is 13:1 in favor of the PPI alternative [40].

Due to factors like that, the German Federal Ministry of Food, Agriculture, and Consumer Protection has recommended using products/components within the economic system for as long as possible, from a high level of value stepwise to lower levels [41].

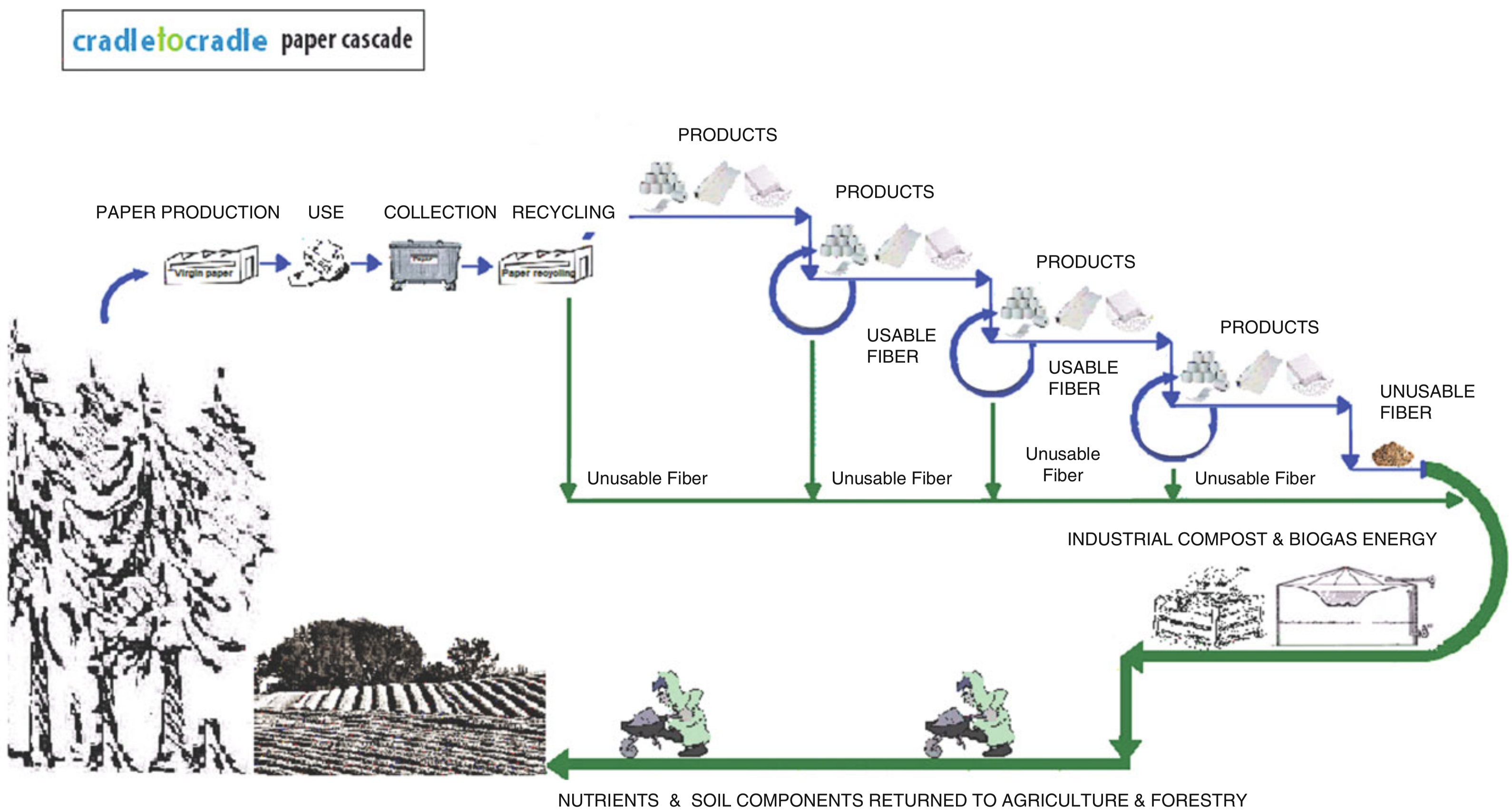
One problem with material cascades is the difficulty of tracing the material as it moves from one use to another. This is especially important to assure that cascades are not misused for downcycling. Nutrient Certificates could be introduced in the cascade process, identifying the cascade supply chain and which stages in the cascade the material has already participated.

Chain of Possession-Tracking Mechanisms It might seem impractical to trace nutrients from bulk materials such as plastics and agro-industry products into more sophisticated complex materials and then into the complex products that may enter a cascade process. However, this form of tracking is already being done to some extent for authenticating mechanisms used to guard against industrial diversion, counterfeiting, and brand abuse [42]. Many companies now offer globalized authentication for a variety of materials ranging from pharmaceuticals to fuel and currencies, with different authentication solutions for different types of materials. Although there is yet no "one size fits all" mechanism to track chain of possession in such a range of materials, the tracking technologies themselves are sufficiently varied and making rapid advances in accuracy as well as affordability to meet this challenge.

Chemical and DNA fingerprinting are advancing quickly as are nano-tagging and electronic micro-tagging, e.g., RFID. These are becoming so sophisticated that they are being used to monitor everything from the origin of oil spills from ships to the origin of uranium in a weapon. Recently, various frameworks have been developed for the management of tagging and tracking systems to support reverse logistics and other chain of possession methods [43]. Large retail chains and manufacturers have sophisticated mechanisms for tracking inventories of component materials used in their products. As well, systems such as Underwriters Laboratory (UL) certifications have been used for years to label and track components in millions of devices. It might be possible to optimize such systems to include Nutrient Certificate-related data.

Building on these systems, a primary implementation path for Nutrient Certificates could be to embed data records in micro-tags that describe "defined-use" standards for recycled and "cascading" raw materials. The data records would complement, not replace, material data safety sheets.

The Potential Role of Buildings for Implementing Nutrient Certificates Nutrient Certificates could be effective mechanisms for transforming buildings and



Resource Repletion, Role of Buildings. Figure 3

Diagram of the potential for using paper in a product cascade (Source: Redrawn from an EPEA drawing [39]) products that move through them to a materials repletion value chain.

Buildings are early candidates for the transition to Nutrient Certificates due to:

- *Value.* Nutrient Certificates represent a way of enhancing the value of buildings for their owners and managers. Instead of materials becoming waste that is expensive to get rid of, they become part of the value chain of the building. This can also enhance property lease and resale value.
- *Tracking.* Buildings involve large material flows that are already quantified in terms of volumes, location, and other specifications. Frequently, inventories are kept of materials used to build, maintain, and operate buildings. These would be transition mechanisms for defining Nutrient Certificate parameters.
- *Chain of Possession.* Institutions such as hospitals, educational institutions, government buildings, large corporations, and airports have extended ownership of their buildings and have a vested interest in maintaining value. They also provide continuity of record-keeping.
- *Volumes.* Building structures use large volumes of materials in one place so it is more convenient to inventory those volumes in one location than trace consumer products that are purchased in small quantities and are transient.
- *Local Material Sourcing.* Many high-volume building materials tend to be locally sourced so it is relatively easy to identify the chain of possession and to go back to the supplier to verify what is in the materials.

Time frame for Recovery of Value from Materials in Buildings Although buildings are perceived as largely longer-term repositories for materials, in reality, many materials used in the construction and operation of buildings have a shorter use period. For example, packaging for construction materials, topsoil removed to make way for new buildings and replaced in the form of landscaping, cleaning products, maintenance equipment, floor coverings, and office equipment all have shorter life cycles. Because of this, Nutrient Certificates can offer economic benefits for building owners and operators early into the process, when materials are transformed from their use in a product to resources for reuse. The resource recovery can occur relatively quickly or may require decades as further discussed below.

Early Candidate Products for Nutrient Certificates in Buildings The "low hanging fruit" for Nutrient Certificates consists of business-to-business materials in buildings that involve a chain of possession where the players are relatively well defined. For example, on the technosphere side, heating, ventilation, and air conditioning (HVAC) equipment and other systems that represent close to half the value of many buildings have defined chains of possession for their component materials, from manufacture through to transport, sales, use, and disposal. Their components are well cataloged for maintenance purposes. "Moveable" office equipments such as photocopiers also have defined chains of possession because they are leased as part of service agreements. On the biosphere side, office paper in large institutions offers chain of possession opportunities because it is collected and reprocessed in large volumes. Interior and exterior landscaping is often maintained as part of service agreements, and these provide a mechanism for quantifying the nutrient contribution of plants and soil. The important characteristic of many of those inventory systems is that they already exist, with accounting systems that can be modified to track and quantify materials. In some cases, individual companies already have a form of Nutrient Certificates for materials used in building interiors, such as the previously discussed Backhausen Returnity® certificates. Less well-defined, but still traceable in large institutions, food waste and sewage can be tracked for organic nutrients.

Early Adopters for Nutrient Certificates in Buildings Because regulatory regimes typically lag behind the science, governments might not be leaders at proactively defining materials. However, governments will be important for advancing recovery of materials as nutrients because they are:

- Good at inventorying what is in their buildings
- Long-term players in the property marketplace
- The owners and occupants of substantial numbers of buildings

Hospitals, educational institutions, large corporations, and airports also are potential early adopters because they have extended ownership of their buildings and a vested interest in maintaining value. One ready-made network of companies exists that is accustomed to the principles and practices underlying a Nutrient Certification system. That is the network of the hundreds of companies working on Cradle to Cradle®-defined products and infrastructures. Nutrient Certificates could be introduced into the supply chain of those companies, involving the thousands of suppliers of those companies as well as millions of customers at the receiving end. In particular, "waste management" companies who are transforming themselves to materials providers are well equipped to implement Nutrient Certificates. For example, in The Netherlands, companies such as Van Gansewinkel Groep have declared their intentions to use C2C application tools in partnerships with customers [45], an important step in bridging the economic intentions of industry with the environmental intentions of customers.

Establishing Bankable and Trading Value Nutrient Certificates do not have to be legislated into existence. Their parameters already provide the marketplace with the motivations, guarantees of content, recyclability, residual value, risk management, and authentication. Governments can accelerate adoption of Nutrient Certificates by specifying them for purchasing, but this is not a prerequisite for their existence.

Nutrient Certificates vs. *Emissions Mechanisms.* One advantage of Nutrient Certificates over emissions trading mechanisms is their connection to traceable materials. When connecting to traceable materials, it is more difficult to distort the marketplace by issuing extra certificates, as occurs with emissions trading. In addition, Nutrient Certificates often quantify what is already given value by the marketplace, so there is no need to match supplies of certificates with, for example, emissions because marketplace mechanisms are already in place to establish value.

Calculating Loss of Value Nutrient Certificates can also be used to calculate *loss of value*. If a material is destroyed, for example through incineration, the certificate is invalidated or modified to reflect the residual value of remaining ash. This procedure is an effective way to measure the true cost of incineration because, presently, the loss of value of millions of tons of materials is not calculated when they are incinerated.

Risk Management Features Nutrient Certificates might on the surface seem to add bureaucracy and costs for the building industry, but in reality, they can do the opposite. By improving the quality of materials, industry can use Nutrient Certificates to:

- Gain added protection from the substantial health liabilities that are arising related to indoor air quality and groundwater pollution. Costs of indoor air pollution to human health have the potential to cripple industries financially.
- Add new value to buildings by enhancing the secondary value of the component materials, which today are often regarded as low value or toxic waste. This "value" can produce benefits only a few years into the operation of a building, when maintenance requirements result in the replacement of damaged and worn out products such as carpeting, lighting, and HVAC components.
- Add new revenue streams from short-term flows of materials through a building. For example, food "waste" from cafeterias and restaurants can be part of materials pooling for industrial composting and biodigestion.
- Add new value to buildings through beneficial functions such as topsoil manufacturing, oxygen manufacturing, CO_2 reuse, energy generation, and recovery of scarce materials.
- More rapidly, amortize the cost of generating electricity by replacing traditional cladding materials with energy-generating materials whose qualities for recycling are defined.
- Cut capital and operating costs through service agreements with companies who lease instead of sell materials and products ranging from office equipment to carpets and power generators.
- Gain emissions credit by defining the greenhouse gas "counter-footprint" of a building more precisely and expanding that counter-footprint to include innovative materials such as cladding materials to generate renewable energy.
- Reducing Risks of Market Distortions. Unlike emissions trading, Nutrient Certificates will make it more difficult to distort markets. When someone acquires a Nutrient Certificate, they will usually be able to check that the material comes along with it, and vice versa.

DBFMO Risk Management New lifecycle costing financial instruments are conducive to the materials-banking approach. For example, in The Netherlands, government buildings are being financed according to a design-build-finance-maintain-operate (DBFMO) approach where a consortium performs each of those functions and is involved in the building for 15–25 years. This provides an extended planning perspective for designing and recovering materials that move through buildings, and an alternative to the typical DBFMO approach of building-in a financial "cushion" to their bids to guard against future unknown cost overruns. Defined materials and related revenue streams can reduce this uncertainty by providing extra value cushions. For example, if the consortium knows it will not have toxic or other waste management costs and has a lower risk of liability from indoor air pollution, this provides a greater level of certainty. If cladding materials are producing revenues from energy generation, the energy benefits will protect against uncontrolled energy price fluctuations.

In those ways, defined materials provide reliability and predictability in the marketplace.

Conclusions

Innovative quality-based approaches including "defined" materials, cascades, and Nutrient Certificates can be used to overcome unintended consequences of traditional approaches to sustainability such as loss of rare materials due to minimization, undefined recycled content, confusion between biobased and biodegradable, depletion from burning virgin biomass, and distortion of markets due to poorly designed emissions credits schemes. The conservatism of the building industry can be advantageous in applying a quality-based approach due to the industry's emphasis on inventorying and value generation. Buildings can thus transcend the current paradigm of materials depletion to become beneficial materials repletion contributors.

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Sustainability Performance Simulation Tools for Building Design

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Article Outline

Glossary

Algorithm It is a step-by-step procedure expressed as a finite set of well-defined instructions for calculating a mathematical function related to data processing and system analytics.

Behavioral model It is a virtual model that aims to abstractly represent a real-world system through one-to-one mapping of parameters that can reproduce the behavior of the original analyzed system. A validated model can uniquely predict the future system states based on past system states.

Building information model It is a digital representation of physical and functional characteristics of a facility based on a standardized representation schema to facilitate collaboration by different stakeholders at different phases of the lifecycle of a facility.

Building life cycle A comprehensive overview of a building delivery process that takes into account the design, construction, commissioning, operation, and decommissioning phases.

Building performance A set of qualitative and quantitative metrics that characterizes the behavior of a building, which includes spatial, thermal, air quality, acoustical, visual, building integrity, and energy efficiency considerations.

Interoperability It is a property of a product or system, that conforms to a certain established standard framework, with clear interface connections to other products or systems, present or future, without any restricted access or implementation.

Ontology It is a formal explicit representation of knowledge as a set of related concepts within a certain domain.

Semantics It is the study of meaning and interpretation of human forms of expressions in terms of words, phrases, signs, and symbols in communication.

Stochastic model It is a representation of a system whose behavior is intrinsically nondeterministic, such that the probability of the outcome of a future state is affected by both the process's predictable actions and by a random element.

Taxonomy It is the practice and science of classification of things or concepts as well as principles underlying such classification.

Introduction

Sustainable building, also commonly known as high-performance or green building, is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction [1]. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Historically, there have been many well-established theoretical frameworks that relate building design with its environmental as well as human occupant performance within those buildings [2–5]. Design decision support tools, both physical and computational, have invariably been developed in accordance with the needs of these respective design processes and, in some instances, directly linked to meeting various building code and standard requirements. Therefore, such tools must be understood and appreciated in the context of the building delivery processes adopted in contemporary practices

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or are being advocated in response to certain prevailing industry-wide mission (such as sustainable design) in a particular historical milieu.

The building delivery process has commonly been regarded as a discrete and sequential set of activities. This state of affairs is the result of a historical evolution driven by many factors. As building design becomes ever increasingly complex due to changing perceptions and demands of developers in a competitive globalized real estate market, specialist professional communities have emerged, bringing specific knowledge input to the building delivery process beyond the capabilities of the conventional architectural and building engineering professions. While this might seem a rational step toward addressing the complexity involved, it also inevitably and fundamentally transforms the originally integrated process to one of fragmentation and compartmentalization. This in turn necessitated the development of communication frameworks based on the organization of activities for the purpose of establishing a professional fee structure that is commensurate with the scope of work and level of accountability or responsibility at various project phases. The quest for more efficient communication methods has gradually evolved into a *circulus vitiosus* whereby advances in communication and dissemination technologies continuously struggle to cope with unprecedented rate of information growth globally, while continuing (if not intensifying) the trend toward process disintegration. Superficial attempts to patch the current decision-making approaches often lead to miscommunication of intentions, resulting in unsatisfactory solutions which are costly to remedy in terms of time and resources.

The capabilities of design decision support tools are nonetheless expanding but they still fall short of anticipating or challenging the very logic of the industry processes they are supposed to support. Among the major industries in any national economy, it is often observed that the building industry is one that is traditionally most resilient to structural change. In particular, its uptake and exploitation of advanced technology of any form is conservative and slow – the common reason given being cost constraint. The availability and affordability of powerful computer systems and software have transformed the way business is conducted in many other fields. Yet the building industry still tends to deploy this technology in a comparatively rudimentary way. However, over the past decade, the sustainable development movement has been gaining unprecedented momentum globally and is beginning to exert a profound influence on coevolutionary development of the building delivery process and building performance simulation tools.

More elaborate discourse in this matter can be found in [6] and [7]. These authors further address the necessary conditions under which significant structural changes in the building delivery process can evolve and the related implications for future development of decision support tools. They also explore hidden potentials of existing tools and propose enhancements to facilitate effective knowledge transfer and process management.

Brief History of Building Performance Simulation

Building simulation as a discipline can be traced back to the 1960s with the US government's projects to evaluate the thermal environment in fallout shelters by an hour-by-hour simulation of heat and moisture transfer process between human occupants and shelter walls under limited ventilation conditions [8]. Kusuda offered an interesting historical account of the building system simulation focusing on the thermal performance domain. Since then, building simulation has been constantly evolving as a vibrant discipline that produced a variety of tools that are scientifically validated across different climatic domains.

According to Clarke [9], there are four relatively distinct generations of energy simulation tools over the past 4 decades. The first generation of tools tend to be handbook oriented that adopt disparate simulation techniques to address piecemeal design exercises. These tools are easy to apply but the results are difficult to interpret. The second generation tools of the mid-1970s began to focus on the temporal aspects of energy simulation by implementing response functions to derive analytical solutions. HVAC system modeling was confined to steady state assumptions. The third generation of the mid-1980s recognized the importance of systems integration in the simulation approach whereby all other system parameters are linked and solved numerically while only space, time, and climate remain independent variables. The first graphical-user interfaces (GUI) began to emerge at this time. The fourth generation tools of the mid-1990s continued to pursue and expand the integration framework. The increasing scale and complexity of such integrated design functionalities necessitate the development of a modeling platform (now commonly referred to as building information model or BIM), to organize, manage, and provide seamless exchange of data between various discrete and yet related building system domains. The GUIs became more user-centered, providing support through embedded knowledge bases in the form of data libraries and design task-oriented guidance.

Meanwhile, other building performance related simulation tools, e.g., in lighting, airflow in and around buildings, moisture flow, and acoustics, have also emerged in the 1980s and are continually being refined. One of the most comprehensive sources of literature that document the evolution of the building performance simulation world can be found in the publication archives of the International Building Performance Simulation Association (IBPSA) [10]. The collection of papers dates back to 1985 when the IBPSA held its inaugural conference in Seattle, Washington, USA. The conference proceedings are organized thematically that covered in the early years a limited range of topics on research and development, validations, applications in industry, and user interface design. As the field continues to evolve, the range of topics have expanded significantly to include detailed simulation of advanced building materials, components and systems, control technologies, occupant behavior, health and comfort, code compliance, as well as macrolevel studies of climates and microclimates, landscape and urban heat island effects, and zero- or low-carbon sustainable developments.

In 2008, IBPSA launched its Journal of Building Performance Simulation [11]. At about the same period, another journal titled Building Simulation: An International Journal [12] was also established. These are important milestones that signify the maturation of building performance simulation into a recognized and indispensable discipline for all professions involved in the design, engineering, operation, and management of buildings. In the twenty-first century, the simulation evolution is dominated by two key processes, namely, (1) attaining an increased level of quality assurance and (2) offering efficient integration of simulation expertise and tools in the overall building process, according to Augenbroe [7]. His paper on *Trends in Building Simulation* offers a detailed overview of the achievements and imminent challenges faced by the profession. It also provides a glimpse into the changing "appearance" of simulation tools that is brought about by the internet revolution, as exemplified by new forms of ubiquitous, remote, collaborative, and pervasive applications. There are also experimental attempts to blur the distinction between real and virtual simulation with the deployment of augmented reality, as described in [13]. This technology can potentially allow an observer to interact with a running simulation of himself and his environment while being immersed in the real environment. The results of the simulation can be overlaid in real time on the sensory input of the immersed observer, e.g., via computer generation of an image on a transparent visor.[1]

Principles of Sustainable Building Design

Four fundamental human-related elements should be contemplated in discussing the process of human involvement in the creation of our built environment: theory and practice – knowledge and experience. These elements are always present, but the degree of engagement varies within individuals as well as collectively within a building design team.

Theory and Practice

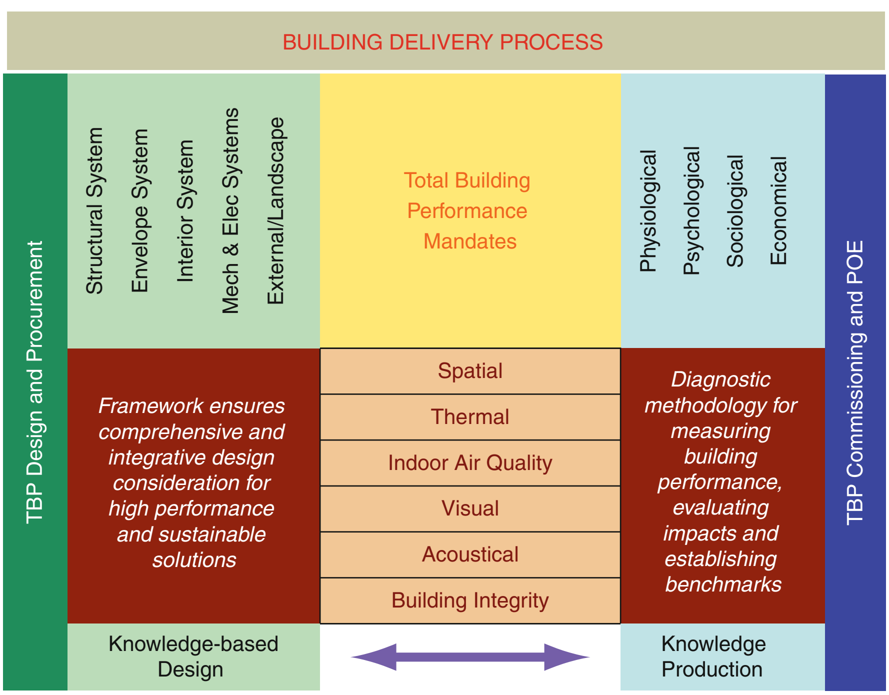
Theories can be regarded as analytical tools for understanding, explaining, and making predictions about a given subject matter, be it in the arts or sciences. Theoretical constructs are particularly helpful when dealing with complex systems involving multidimensional and multi-domain interactions. It should be noted that a theory is syntactic in nature and is only meaningful when given a semantic component by applying it to some content (i.e., facts and relationships of the actual historical and physical world as it is unfolding) [14]. Green building design is a good case in point.

Green building, also commonly known as sustainable or high-performance building, is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction [15]. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. There are many "traditional" theories that relate building design with its environmental as well as human occupant performance within those buildings [16, 17].

A specific example of the performance-based approach to design is a well-established model based on the concept of total building performance and diagnostics (TBPD) [18] (Fig. 1). This concept was originally advocated by a research team at Carnegie Mellon University, USA, in the early 1980s. TBPD is an integrated and holistic knowledge-based framework for conceptualizing, specifying, designing, analyzing, and commissioning a building project. It can provide a comprehensive brief for a client and the project team who are committed to quality and high-performance goals throughout the project duration, from inception to completion, and can even extend to post-occupancy management and maintenance. It can facilitate optimization of the design performance, avoidance of conflicts, elimination of omissions and abortive work, and wastage of resources.

It embraces six principal performance mandates, namely, spatial, acoustical, thermal, visual, indoor air quality, and building integrity. Each mandate comprises a set of performance targets and pertinent diagnostic tools. The targets are occupant-oriented deliverables that pertain to the environmental or physical attributes of the building which impact the physiological, psychological, social, and economic well-being of the occupants. The diagnostic tools are methodologies developed for the appraisal of the building design in terms of the various performance indices.

TBPD is not just about the application of "hi-tech" building systems and/or materials. It seeks to rationally and systematically exploit the synergy of the various relevant technologies and management know-how to



Sustainability Performance Simulation Tools for Building Design. Figure 1
Total building performance and diagnostics concept

bring about desirable building performance at a reasonable cost. Knowledge and experience of an integrated team are clearly essential ingredients within the strategic framework. The ultimate success of a sustainable and high-performance building may be assessed by considering how well it meets the following four principal criteria: (1) occupant satisfaction, (2) organizational flexibility, (3) technological adaptability, and (4) environmental and energy effectiveness.

Knowledge and Experience

Louis Sullivan defines architecture as the crystallization of the thoughts and feelings of a civilization. There is a long tradition in the architectural world of tracing and documenting the changes in building design over the ages and in different geographical, climatic, and sociocultural and even political contexts. Such efforts in the realm of history and theory of architecture tend to focus predominantly on the arts and humanistic aspects. Literature that rigorously records the building-related sciences and technologies of the times is comparatively rare. Occasionally, it is possible to get a glimpse of the work of the ancient master-builders and the incredible technical ingenuity that created architectural masterpieces that is "sustainable" in every sense by today's [re] definition of the term. Knowledge and experience are produced, preserved, and transmitted through the generations often by long-suffering apprenticeships. Arguably, life was simpler and the palette of options was limited in comparison to our modern globalized world but that was not necessarily a disadvantage and certainly did not hamper the creative and innovative spirit that existed during those past milieus.

Witnessing phenomenal advances in science and technology in the world, the building industry at large remains very slow in responding to or capitalizing on the tremendous potentials and opportunities offered compared to other industries or businesses. Building performance–related research is not particularly valued by the industry and society, and consequently, support for such endeavors is dismal. Despite the circumstance, there have been research activities that generated a significant body of knowledge over the past 3–4 decades, way before green design became a contemporary buzzword. However, this knowledge is invariably lodged within highly technical publication archives that continue to serve the academic and research communities but rarely touch the practice world in any meaningful or impactful way. As the knowledge base continues to expand, it is inevitable that the chasm between "what is known" and "what is done" becomes increasingly wide.

Recognizing this state of affair, the building industry then attempts to ameliorate the consequences by simplifying the inherently complex relationships and interactions between humans and the environment in the form of prescriptive solutions that get codified into standards and regulations. Simplification and prescriptive approaches are not inherently bad in themselves and they do provide a cost-effective means of setting certain critical performance benchmarks in building. However, there are always limits of applicability and embodied assumptions that are not often immediately apparent to designers who are increasingly more likely to operate in a globalized practice.

This then leads to the final human element of experience in this discussion. Even in this realm, the building industry is unbelievably weak in "professionalizing" this valuable human resource. The medical and the law industry, two rather diametrically different professions one may add, share a common unifying practice of systematically and meticulously documenting their "experiences" – both the good and the bad as well as the success and the failures. These become the tangible and valuable industry assets that society has come to accept and somehow has to pay for. Whether it is attributable to the educational system and/or a deeply entrenched business structure, the building industry is highly fragmented and often adversarial rather than collaborative in nature. For the fear of professional and financial liability, cases of failure are often buried through private settlement. Experiences gained from such events therefore reside only with the parties involved and not generally accessible for the industry to share and learn from. Even if there is no catastrophic encounter, there is currently no widely adopted practice of monitoring and measuring the performance of buildings in use and comparing the empirical results with the predicted design performance targets. Much can be learned from such provisions and they can also open up new innovation pathways into the field of real-time intelligent sensing and predictive optimal building control. Unless there is some fundamental paradigm shift in professional practice, especially to address the specific challenge of green building design and operation, the industry may well be condemned to the "Sisyphean task"[2] for a long time to come.

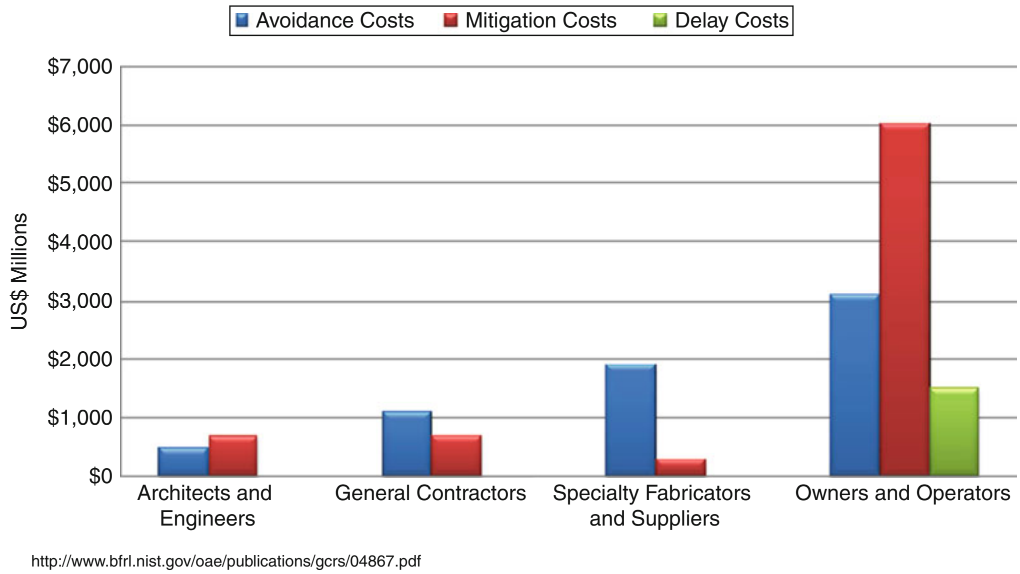
Prerequisites for Building Performance Modeling

An effective process of sustainable building design requires engaging the elements of theory, practice, knowledge, and experience through integrative inputs from multidisciplinary professional teams. Effective communication through information exchange is an important success factor. A study from US National Institute of Standards and Technology shows that 30% of the construction cost is lost due to the information interoperability problem among the building delivery team [19] (Figs. 2 and 3). There is national interest in the USA to strategically address this issue that affects the quality of buildings being designed and constructed as well as productivity loss in the industry.

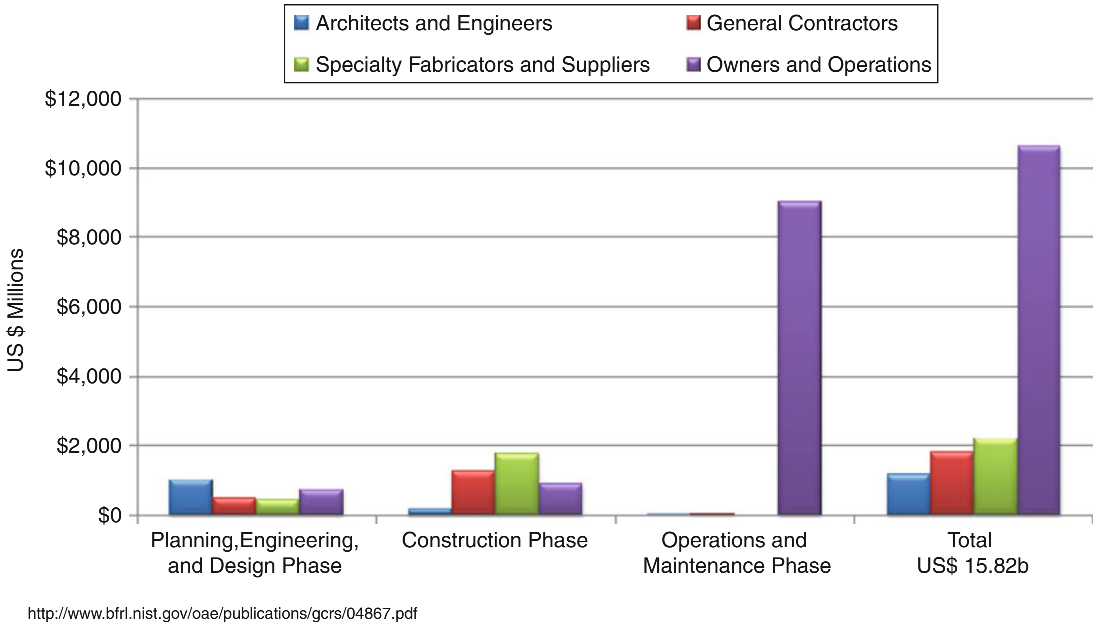
A multi-prong strategic approach has to be adopted to revolutionize the building industry and to change the "business-as-usual" mindset. It must concurrently address the processes and products involved in green building delivery, and the nature of the hardware, software, and human resources associated with the respective functions. Education is perhaps the most critical starting point to address the fragmented infrastructure as illustrated by Mattar [20] (Fig. 4) and effect lasting change. While architecture is traditionally regarded as "the art and science of building," architectural education around the world is still seeking the balanced curriculum that provides a firm foundation in both the qualitative and quantitative elements of design creativity. The sustainability movement has yielded new and widely recognized building performance standards (e.g., LEED) that are leading building developers to demand design teams to achieve such standards in order to remain competitive in the real estate market. Industry drivers are in motion to hasten the curricula and pedagogical change in schools of architecture and engineering.

Modeling and Simulation

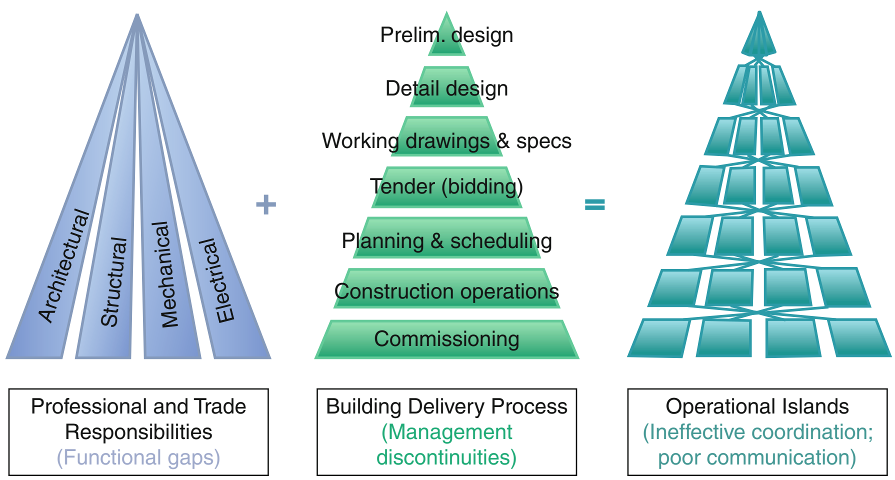
Simulation is the process of designing a model of a real or imagined system and conducting experiments with that model. The purpose of simulation experiments is to understand the behavior of the system or evaluate



Sustainability Performance Simulation Tools for Building Design. Figure 2
Cost of inadequate interoperability by stakeholder group and cost category



Sustainability Performance Simulation Tools for Building Design. Figure 3
Cost of inadequate interoperability by stakeholder group and building life cycle phase



Sustainability Performance Simulation Tools for Building Design. Figure 4
Building industry infrastructure (cp. Mattar [20])

strategies for the operation of the system. Assumptions are made about this system and mathematical algorithms and relationships are derived to describe these assumptions – this constitutes a "model" that can reveal how the system works [21]. Simulation is deployed when the real system cannot be engaged, because it may not be accessible, or it may be dangerous or unacceptable to engage, or it is being designed but not yet built, or it may simply not exist [22]. It can be used to demonstrate the eventual "real" effects of a system when subjected to alternative conditions and courses of action.

Building performance models are developed by reducing real-world physical entities and phenomena to an idealized form on some desired level of abstraction. A classic overview of modeling tasks in the building physics domain can be found in Clarke [9]. Design analysis supported by simulation involves the creation of a behavioral model of a building in a given stage of its development, e.g., reflecting its "as-designed" or "as-built" or "as-operated" specification. The actual simulation involves executing this model on a computer, analyzing its observable states, and mapping these observations to suitable quantifications of performance indicators, e.g., by suitable postprocessing of the outputs of the simulation runs [7].

Critical Elements of Integrated Process and Product Modeling

Data Sharing and Interoperability It is encouraging to note that in the past decade, the building industries in many countries have begun to seriously adopt IT within an integrated and systematic framework that covers the building life cycle, from inception to design, construction, post-occupancy operations, and eventually demolition and recycling of building materials.

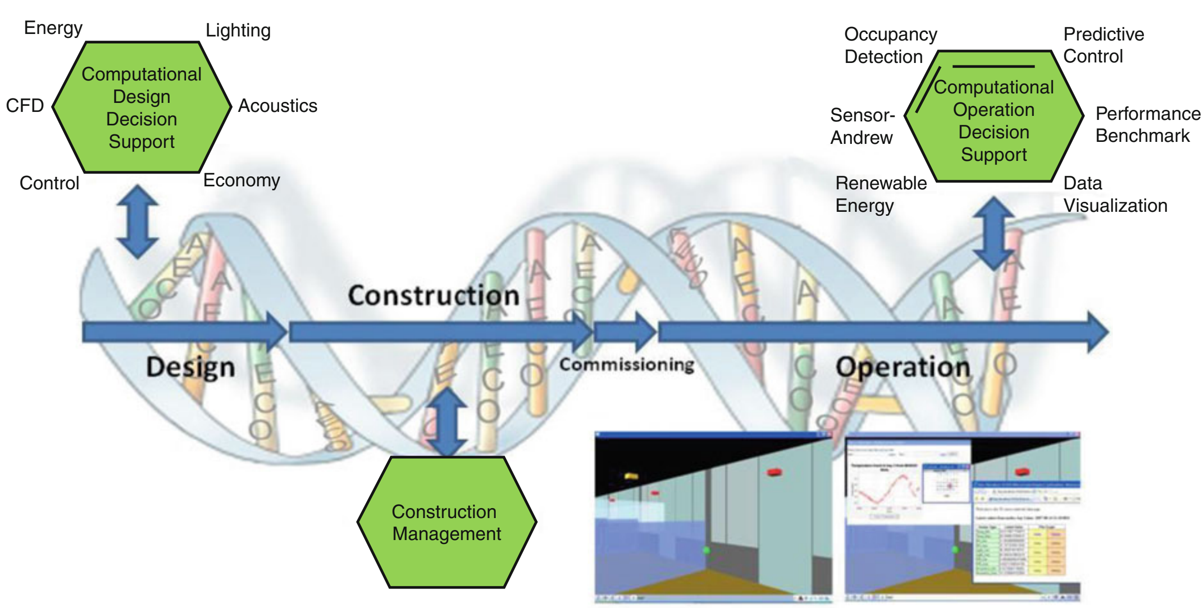
A significant catalyst of this movement is the establishment of the International Alliance for Interoperability (IAI), which originated from the USA in 1993. It has since been renamed as buildingSMART International and currently has 15 chapters in North America, Europe, Asia, Australia and Middle East with more than 600 member organizations and companies [23]. One of its mission is to define, publish and promote standard specifications for industry foundation classes (IFC) as a basis for information sharing throughout the project life cycle (including facilitating e-procurement of project-related goods and services), and across all disciplines and technical applications in building industries worldwide. IFC, essentially an object-oriented data model schema, enables interoperability – an environment in which IFC-compliant computer programs of any kind (e.g., CAD, specification documentation, building performance simulation and facilities management software) can share and exchange data, regardless of where the data may be residing. They are information-rich, comprising physical and other attributes that can be shared throughout the supply chain. Data pertaining to a project can be seamlessly organized and linked for ease of communication during the design and construction process, and subsequently archived for future reference by building owners and operations management. Such a data schema forms the core of what is now commonly known as building information modeling or BIM.

Building Information Modeling In the USA, a National Building Information Modeling Standard (NBIMS) has recently been published [24]. This standard is intended to provide the framework and foundation to encourage the flow of information and interoperability between all phases of facility's lifecycle. It defines BIM as "a digital representation of physical and functional characteristics of a facility" and its overall scope is to facilitate "collaboration by different stakeholders at different phases of the lifecycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder" [23].

The key attribute of a BIM is its ability to organize and relate information for both users and machine-readable approaches. However, to enable interoperability between applications and databases, the inherent semantics of the underlying taxonomy and ontology have to be unambiguous and nonredundant. One of the primary roles of the NBIMS is to provide the ontologies and their associated common languages that will allow information to be machine-readable across different but related domains. NBIMS presents an excellent conceptual model of information exchange in AEC industry. The question then is what approach can be adopted to develop an operative IT platform to realize and implement this conceptual model in practice. Current BIM development work tends to be focused on the design and construction phases (and with minimal interoperability for integrative performance simulation support) but not yet extended to consider ongoing performance monitoring and diagnostics throughout the life cycle of the building. Particularly for complex buildings, effective operations have significant impacts on ensuring that the predicted design performance is actually achieved and sustained throughout the building life cycle. Therefore, a comprehensive dynamic life cycle building information model for the "total building performance and diagnostics" approach is advocated to address the entire building delivery process and ongoing commissioning of high-performance buildings. The model structure is based on the industry foundation class (IFC) schema (as endorsed by NBIMS) that will capture (a) "static" building information generated during the design and construction process and shared among the design architects and engineers particularly to support building performance predictions using various building simulation tools, benchmark evaluations (e.g., LEED), and advanced design optimizations; (b) "dynamic" (operational) building information generated from large-scale occupancy detection and environmental sensing network for ongoing commissioning, whole building performance monitoring, and advanced adaptive controls based on occupant behavioral studies. This integrated model will also serve as a rich repository of comprehensive evidence-based case studies for ongoing research and development as well as education of professionals for the building industry in the long term (Fig. 5).

Building Performance Modeling While the BIM development work continues, many well-established advanced "stand-alone" performance modeling tools are readily available for use by design teams. The following discussion highlights some of the critical areas of input especially from the architect working within the team. Whether or not the architect personally conducts the modeling work, these points of considerations are vital and must be clearly established for the team. Otherwise, the age-old ugly truth of computing will prevail – garbage in, garbage out (GIGO).

Determining Occupancy Schedule Building performance simulation aims to support sustainable design and the creation of healthy, comfortable, and productive habitats for human activities while minimizing resource utilization and waste generation. Ironically, defining such human activities "accurately" as input factors in performance modeling remains probably the single most complex and challenging task. For example, research has shown that for a variety of reasons, actual occupancy rate in modern office buildings is frequently only 40–60% of the design assumption. This has consequences not only on energy consumption but also on the maintenance of comfort conditions in buildings. Mismatch between designed and actual operating conditions results in excessive



Sustainability Performance Simulation Tools for Building Design. Figure 5
Dynamic Life Cycle Building Information Model (DLC-BIM) in support of an integrated and sustainable building delivery and operation process. (Architecture, Engineering, Construction, Operation – AECO – the "genetic DNA" of DLC-BIM)

provision of heating/cooling and difficulty in optimizing control of building systems. This challenge lies squarely with the architect, whose responsibility is to thoroughly understand the client's operational requirements and translate that "qualitative" descriptive brief into an architectural design solution, accompanied by appropriate quantitative parameters that can be communicated to the engineering design team members for producing concurrent technical solutions. Recognizing this crucial communicative role should prompt architects to play a more proactive leadership role in building performance modeling.

Configuring Thermal Control Zoning Architects and HVAC engineers typically have quite different notions about "zoning" in a building. One views these zones as formal, spatial, and functional demarcations which may be subject to certain design codes such as fire compartmentalizations while the other regards them as volumes that require conditioning according to a desired set-point temperature. The usual HVAC design objective is to size the systems and configure the layout so as to meet peak load conditions while minimizing the number of discrete control zones as far as possible to save on cost. It is not uncommon to witness inadequacies and conflicts in operational control of the systems when there is a lack of cross-disciplinary understanding and communication during the design stage. Coupled with the uncertainties of occupancy schedule mentioned above, the systems may not be able to respond optimally, resulting in energy inefficiency and uncomfortable indoor environment.

The theoretically ideal approach is to map the "architectural" zones which are subjected to difference in location-based exposures according to orientations (e.g., perimeter versus internal core zones) with the thermal control zoning configuration in the building. Possible design solutions can then be generated through parametric energy simulations and an "optimal" decision can be derived through systematic analysis and evaluation of the quantitative results.

In reality, any simulation result is only as good and reliable as the assumed input values for the various parameters. However, if the model is constructed based on "first principle" integrated approach mentioned above, there would be built-in capabilities in the systems for further fine-tuning of the controls when the completed building is in operation. Looking beyond current practice, there are already R&D efforts to "automate" such fine-tuning based on continuous concurrent sensing of the indoor environment and monitoring the system performance as well as micro-climatic conditions throughout the life cycle of the building. The empirical data acquired is the "real deal" and when used as input into a predictive control model, further realistic optimization of the system can be achieved with even greater energy saving. This subject will be further elaborated in section "Integrated Building Design and Operation Process Modeling."

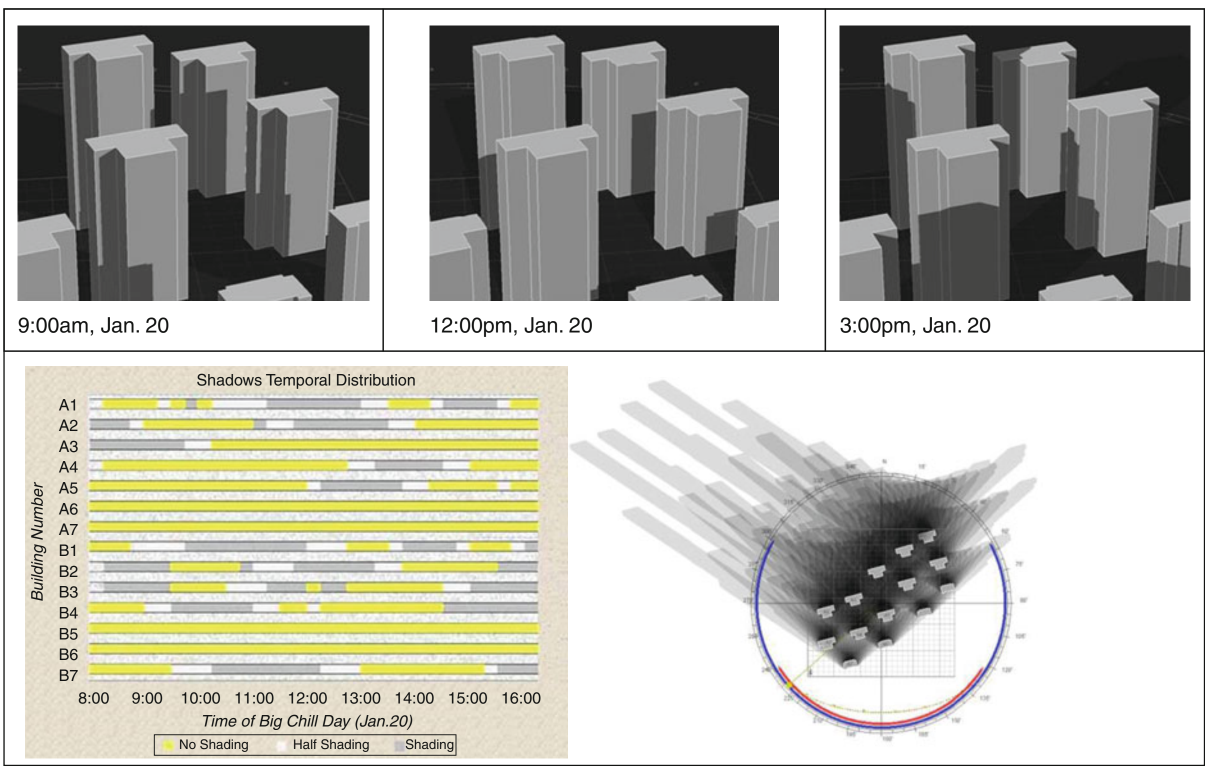
Concurrent Modeling of the Building and the Surrounding Physical and Environmental Context Traditional environmental performance modeling tends to focus mainly on active systems within a "closed" building that rely completely on energy to provide some form of conditioning all year round. Green building design calls for a radical departure from that rigid approach and encourages the exploration of multi-modal environmental control systems in buildings. These would include passive systems that require no energy for operation (e.g., sunshades for solar control, operable windows for natural ventilation, light shelves for daylighting enhancement, etc.), the common active systems as well as mixed-mode conditioning that selectively combine the passive and partially active systems for optimal effects. Furthermore, the concern also extends beyond the performance of the building itself to its potential impact on the surrounding ecological and environmental conditions. The critical consideration for such a holistic design approach necessitates the design team to be fully cognizant of the physical and micro-level environmental conditions surrounding the proposed building, whether present or anticipated (to the extent possible) in the future.

The model should then include every object within the physical domain that will conceivably impact the overall performance outcome. Given that external climatic conditions are naturally dynamic, the parametric study should be carefully structured in order to provide design decision support performance data that sufficiently represent the probabilistic occurrence under the varying conditions over the year or seasons or even at a higher periodic resolution as each case may demand.

Modeling examples of two performance domains (daylighting and natural ventilation) are presented here. Figure 6 shows the sunshine availability and temporal distribution analysis on a multi-block residential development in the Tianjin Eco-city in China. Figure 7 shows the concurrent analysis of daylight factor and daylight illuminance for the same development in meeting China's GB/T 50378: 2006 Evaluation Standard for Green Buildings.

Figure 8a illustrates the concurrent computational fluid dynamics modeling of site and building interiors for the same residential development in Tianjin Eco-city. Figure 8b shows the resulting velocity fields, temperature profiles, and air change rates under different wind directions at an assumed wind speed of 2 m/s. Figure 8c shows the comparative analysis of airflow patterns, assuming same window opening configurations but different interior door opening conditions, under the same external wind conditions. As would be intuitively expected, the results clearly illustrate the importance of considering not only the "static" physical building layout but the inclusion of the "dynamic" configurations under different in-use conditions.

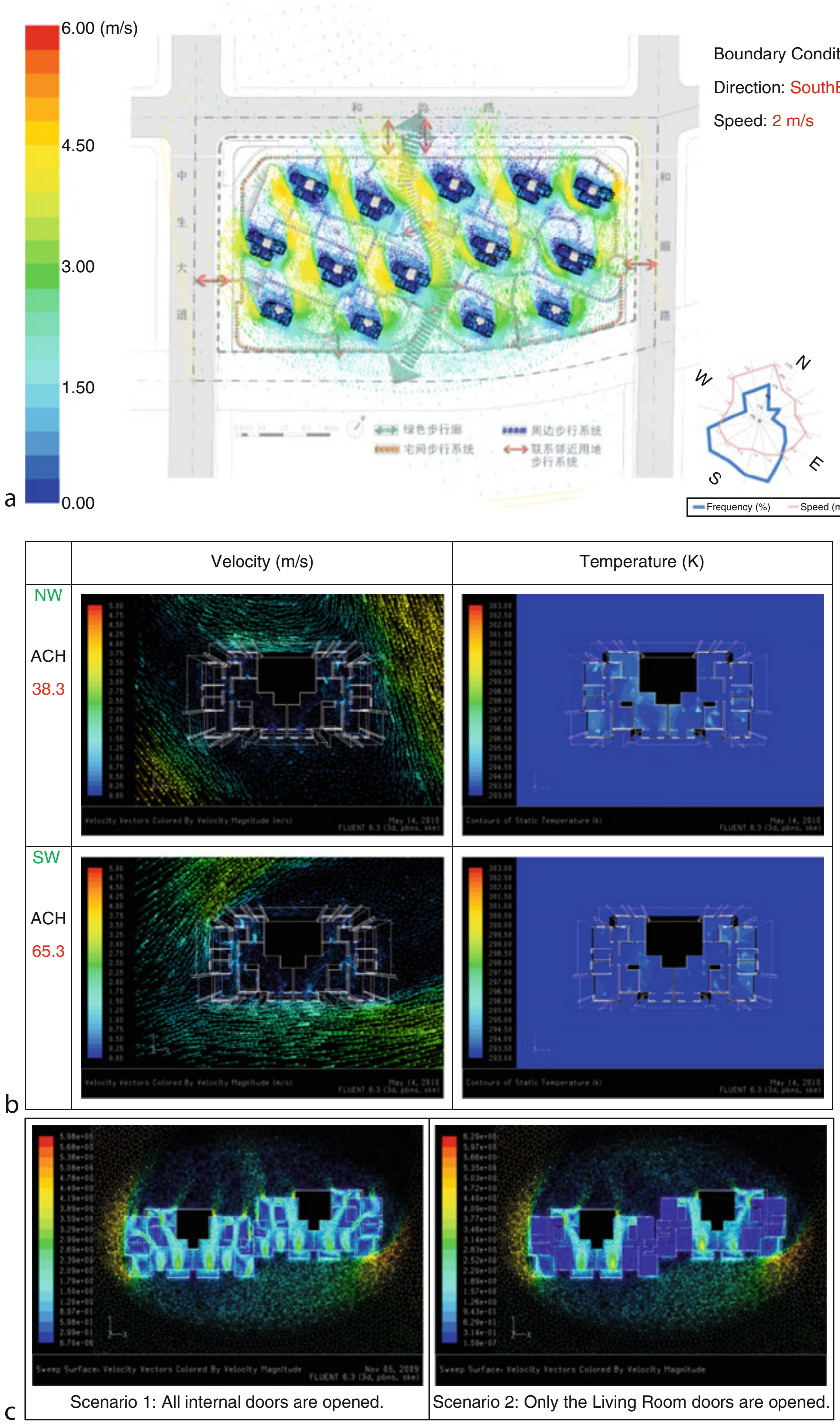
Allocating Resources for Modeling in Early Design Stage The predominant factor in the decision-making process in practice is still based on cost, more specifically first cost. Traditional processes often ignore the operational and occupancy implications while emphasizing first cost despite the fact that tools are available for evaluating cost benefits of a performance-oriented approach to the building delivery process over the life cycle of a project. Yudelson notes that increased economic benefits are the prime driver for change for green buildings. The business case for green development should be based on a comprehensive view of benefits that include economic, financial, productivity, risk managements, public relations and marketing, and funding [5]. It is well acknowledged that decisions at the early project



Sustainability Performance Simulation Tools for Building Design. Figure 6
Sunshine availability and temporal distribution analysis of a multi-block residential development in Tianjin Eco-City, China [25]

Sustainability Performance Simulation Tools for Building Design. Figure 7
Concurrent analysis of daylight factor and daylight illuminance for the multi-block residential development in Tianjin Eco-City in China in satisfying China's GB/T 50378: 2006 evaluation standard for green buildings [25]

phase can have significant impact on subsequent alternatives and design solutions. But the unwillingness to invest in preliminary investigative design studies in order to keep costs low would invariably result in remedial or even abortive work, thereby increasing the overall costs toward the end of the project phase. The range and nature of existing design support tools that are being applied in practice clearly reflect this scenario, whereby they are almost exclusively developed for the back-end of the design and construction process,



Sustainability Performance Simulation Tools for Building Design. Figure 8

(**a**) Concurrent computational fluid dynamics modeling of site and building interiors [26]. (**b**) Velocity fields, temperature profiles, and air change rates under different wind directions at an assumed wind speed of 2 m/s. (**c**) Air flow patterns assuming same window opening configurations but different interior door opening conditions under same wind conditions primarily for design verification rather than design generation. It is therefore of strategic advantage to reassess the relative importance of early conceptual design within the whole and to allocate adequate resource toward this stage of work, and to utilize the potential of computer-aided information-processing tools to support a more comprehensive design/construction strategy.

Performance-Based Versus Prescriptive-based Design

There is a trend in building design toward a performance-based rather than the conventional prescriptive-based approach [27]. Advances in computer technology and, perhaps more importantly, the affordability of such powerful technology have made it feasible and cost effective to use computational design support tools to conduct parametric performance studies of various design options, even at the preliminary design phase.

To further encourage the use of performance-based simulation tools, it is essential to shift the current regulatory systems from prescriptive- to performance-based approach. This shift is not a recent phenomenon as the evolution of building legislation from the practice of prescriptive requirements to performance-based solutions has taken place over the last 10 years or so in countries such as Australia [28]. Though the traditional prescriptive approach is relatively simple to understand, and the requirements are treated as "rules" to be complied with, its provisions are often regarded as "cumulative, conservative in nature and in reality only suitable in relation to 'standard' building configurations" [29].

On the other hand, the basic concept of a performance-based approach is not to prescribe solutions but rather to demonstrate that the proposed design meets defined objectives. This approach may result in alternative designs which are more flexible, rational, innovative, and cost effective. This approach can also be multidisciplinary, consciously taking into consideration the implications and synergistic effects of the various performance mandates. A comprehensive performance-based approach necessitates the ability to translate the objectives into quantifiable parameters, to set limits for these parameters, and to have means of estimating performance of proposed design to validate compliance with the required performance parameters [30]. In this respect, simulation tools should be able to play vital roles in achieving such objectives.

Building Energy Simulation Tools

One of the best overviews of the currently available tools can be found on the US Department of Energy Web site: http://apps1.eere.energy.gov/buildings/tools_directory/subjects_sub.cfm [31]. The list reveals that the emphasis has expanded from an early focus on energy consumption to many other related building performance characteristics.

Majority of the tools are developed to address the increasingly complex requirements of the design and evaluation of commercial buildings. Such complexity arises from the changing perception and demands of building owners, facility managers, and tenants with regard to green/sustainable developments and life cycle operating costs (concerning energy use, in particular) as well as a growing awareness of the potential impact of buildings on human productivity, health, and security.

It is well recognized that the key to influencing the building costs and its performance standards (including energy performance) lies at the early stages of a building project's life cycle [32, 33]. Given the complexity involved, there is a need for effective and efficient tools to assess energy impacts early in the conceptual design phase of a new commercial building design process. Some tools currently exist in various stages of development and targeted for different types of applications and users. There is a need to assess what are currently available and, where necessary, make recommendations for improvements to the tools to facilitate their use in the industry.

Application of Energy Modeling Tools in Industry

An industry survey by Wong et al. [34] of the use of performance-based simulation tools for building design and evaluation concluded that usage of tools remains very limited due to several factors: (1) inherent technical limitation of the software, (2) emphasis on initial or capital cost by clients, (3) a fragmented building delivery process that does not routinely include quantifiable assessments of design options by the design team, and (4) the prescriptive nature of current building codes and design guidelines do not promote analytical use of these tools. The paper also provides a comprehensive list of the well-known simulation tools for energy and HVAC system analyses available in the building industry, providing brief descriptions of the program features and results output. However, commonly deployed energy-related software tools in industry have been dominated by those used for the analysis of energy consumption, selection, and sizing of HVAC equipment by the HVAC designers. Most of these tools are, as mentioned previously, developed for the purpose of design verification and to meet building code requirements at the end of the design phase. They do not necessarily provide "active support" particularly for the early design process.

These points are also echoed in an internal study by the Public Works and Government Services Canada [35]. The study included eight building energy simulation tools (namely, Energy-10, RETScreen, EE4 CBIP, Visual-DOE, BLAST, DOE-2, EnergyPlus, and ESP-r) which focused mainly on their functionalities. The purpose was "to contribute to an increased understanding of energy techniques and consequently, to more rational decision making in building design" among the designers and engineers at PWGSC.

With the increasing consciousness and demand for sustainable building design solutions, the U.S. Green Building Council has provided a national standard for what constitutes a "green building" – the Leadership in Energy and Environmental Design (LEED™) Green Building Rating System. It contains a prerequisite requirement of minimum energy performance for new construction and major renovations. Recommended potential technologies and strategies include the use of a computer simulation model to assess the energy performance and identify the most cost-effective energy measure and quantify energy performance compared to the baseline building. The latest release of LEED V3 incorporated technical advancements to the rating system, offering enhanced online access and help features as well as an expanded certification infrastructure based on ISO standards, administered by the Green Building Certification Institute (GBCI) for improved capacity, speed, and performance [36]. This is a major impetus in promoting the use of energy modeling tools in design.

Besides LEED, there are also other commercial sector endeavors that work to streamline the process of energy ratings for both commercial and residential buildings. One such well-established program is the Residential Energy Services Network (RESNET) [37]. RESNET has just launched the Commercial Energy Services Network (COMNET), which is a new system assessing the energy efficiency of commercial and multifamily buildings. COMNET has published a manual titled "Commercial Buildings Energy Modeling Guidelines and Procedures" [38]. It offers guidance to building energy modelers, ensuring technically rigorous and credible assessment of energy performance of commercial and multifamily residential buildings. It provides a streamlined process that can be used with various existing modeling software and systems, across a range of programs. Notably, the COMNET guidelines will offer applicable procedures for owners to demonstrate that their buildings qualify for federal energy efficient building tax deductions per Section 179 day of the Internal Revenue Code. The guidelines can also be used in calculating percent energy savings for point eligibility for green building rating systems, and in modeling annual energy consumption for use with building energy labels.

Definition of Early Design Phase and Application of Tools

While the term "early design phase" is very commonly used in discussing the building design process, it invariably refers to the stage of work where initial design ideas are being conceptualized in tandem[3] with the formulation of the building project requirements. It is generally recognized that this is an adaptive-iterative process [6]. However, it is often not clear in practice when this phase ends and the next begins.

One essential reference to establish a professional practice definition of early design is the American Institute of Architects Contract Documents. The AIA standard form of contract (see Fig. 9) includes the provision for Energy Studies and Report under the category of planning and evaluation services. The description of supplementary services further describe Energy Studies consisting of special analyses of mechanical systems, fuel costs, on-site energy generation, and energy conservation options for the Owner's consideration. The description of Schematic Design Document also includes electronic modeling. There are also considerations of copyright of electronic documents associated with computational modeling work. These are covered in the Owner-Architect Agreement shown in Fig. 9.

Architect's Services

B141 - 1997 (Owner-Architect Agreement)

Identifying the services needed for the project: Under the Categories of Planning and Evaluation Services *Energy Studies and Report.*
Design Service Articles 2.4.2.1 (p.896): Schematic Design Document may include study models, perspective sketches, *electronic modeling* or combination of these media. Preliminary selections of major building systems and construction materials shall be noted on the drawings or described in writing.

B163 - Part2 (Description of Designated Services for Owner-Architect Agreement)

Article 2.3 – Description of Designated Services:

Project Administration and Management Services - .01 Project Administration – *02 – Research*
Design Services - .23 Architectural Design/Documentation - *.07 Study model(s)*
Design Services - .25 Mechanical Design/Documentation - .01 (Schematic Design Phase) - *.01 Energy sources, .02 Energy conservation* and .02 (Design Development Phase)-*.07 Energy conservation measures*
Design Services - .31 Materials Research/Documentation -.01 (Schematic Design Phase) - .02 Investigation of availability and suitability of alternative *architectural materials, systems and equipment.*

Article 2.4 – Description of Supplemental Services:

Supplemental Services - .54 Special Studies consisting of investigation, research and analysis of the Owner's special requirements for the Project and documentation of findings, conclusions and recommendations for: - .01 Master planning *to provide design services relative to future facilities, systems and equipment* which are not intended to be constructed as part of the Project during the Construction Phase. .02 Providing special studies for the project such as *analyzing acoustical or lighting requirements,* record retention, communications and security systems.

Supplemental Services - *.68 Energy Studies* consisting of special analyses of mechanical systems, fuel costs, *on-site energy generation and energy conservation* options for the Owner's consideration.
Supplemental Services - *.78 Computer Applications* consisting of computer program development and/or computer program search and acquisition, plus on-line computer time charges, for: *.08 Architectural analysis and design ; .10 Mechanical analysis and design; .11 Electrical analysis and design.*

Copyright of Electronic Document

B141-1997 (Owner-Architect Agreement)

(P.2) Terms and Conditions
Articles 1.3 contain the "ground rules" of B141, and embodies a number of notable changes from earlier editions. *One such change involves the architect's drawings, specifications and other documents, now defined as "Instruments of Service", which specifically includes documents in electronic form. The owner's right to the use of such documents (and architect's consultant's rights in documents they have prepared) have been clarified by means of nonexclusive licenses.* In place of "basic" and "additional" services, circumstances are identified that may give rise to change in the architect's services, thereby entitling the architects to additional compensation or additional time for performance. Provisions for dispute resolution now include mediation. Provisions for dispute avoidance include a wavier of consequential damages. The waiver is intended to prevent the escalation of dispute by limiting parties to direct damages resulting from a breach. Finally, grounds for termination are clarified, and the owner is given the right to terminate for convenience.

Sustainability Performance Simulation Tools for Building Design. Figure 9
(Continued)

(P.18) Technological advances, such as computer-aided design, have and will continue to have an impact on the architect's services and the manner in which they are provides. *The architect's services are reflected in instruments of service*, such as drawings, specifications, *electronic data* and interpretive sketches which help the owner to reach the final result, a building project. *Because the use or misuse of the architect's instruments of service affects specific rights and obligations of the owner, the construction team and the public, the architect as a licensed professional retains ownership of, control over and responsibility for these documents.*

(P.19) 1.3.2 Instrument of Service: 1.3.2.1 Drawings, specifications and other documents, including those in electronic form, prepared by the Architect and the Architect's consultants are Instruments of Service for use solely with respect to this Project. The Architect and the Architect's consultants shall be deemed the authors and owners of their respective *Instruments of Service and shall retain all common law, statutory and other reserved rights, including copyrights.*

(P.20) *Given the rapid pace of technological changes, it is not practical to address all the varieties of electronic documentation in a standard form document. The parties may wish to develop a separate, written agreement on how to deal with the electronic formats they may use.*

(P.21) 1.3.2.4 Prior the Architect providing to the Owner any Instruments of Service in electronic form or the Owner providing to the Architect any electronic data for incorporation into the Instruments of Service, the Owner and Architect shall by *separate written agreement* set forth the specific conditions governing the format of such *Instrument of Service or electronic data, including any special limitations or licenses not otherwise provided in this Agreement.*

Sustainability Performance Simulation Tools for Building Design. Figure 9
Summary of contractual provisions in the AIA contract document for conducting energy studies in architectural practice

Given these contractual provisions and the drive toward greener designs, it is envisaged that the use of energy modeling tools will become more pervasive in due course. The critical challenge then is to ensure the available tools are indeed effective in supporting the design process.

Many energy modeling tools have been developed over the years by research and development teams in academia, public agencies as well as the private sectors around the world. The conceptual approaches adopted and technical implementation of these tools vary significantly. Some tools employ "simplified" methods that address specific perceived needs of the early design phase while others adopt complex first-principle-based engineering algorithms that can meet detailed design requirements. The potential for continuous development of any of these tools depends largely on the software engineering paradigm adopted, which should consider both data modeling and activity modeling for the entire design process.

In building performance modeling, the fundamental data required may be categorized as contextual (e.g., geographical and climatic), formal (e.g., geometric configuration and orientation), semantic or attributive (e.g., dynamic material properties), and performance indices (e.g., energy consumption targets and code requirements). Activity modeling should recognize the growing necessity to support multidisciplinary collaborative design as building projects become more complex [39]. With increasingly affordable computing power, it is argued that energy modeling tools should adopt rigorous physics- and engineering-based algorithmic principles in the computational prediction of energy performance to ensure acceptable results.

The different functions within a particular design phase can be met through the user interface design which could progressively reveal different levels of pertinent information input demands with associated library support, and generate appropriate output information to assist in decision making at that particular stage. For example, at the early design phase, the architect may explore various building geometries, orientations, and fenestration configurations, and be provided with recommended input parameters derived from an extensive contextual case-based library support in terms of materials, construction, performance targets, etc. The output required at this phase may just be building loads without detailed considerations of mechanical systems and actual energy consumption. As the design progresses, the design team can then be exposed to greater degrees of freedom, with commensurate application support, in modifying the input parameters, not only in terms of the data model but also in computational algorithmic options that aim toward increasing levels of accuracy and resolution as well as performance details in the results output.

Literature Survey of Some Existing Energy Modeling Tools

As part of a research project titled "Energy Modeling Tools for Early Design Phase" [40], a literature review was conducted on the more well-known energy modeling tools that exist. These tools vary tremendously in many respects. A comparison of the 22 tools was made based on the following criteria:

User interface
CAD interface
Ease of use
Manuals
Computer platform
Expertise required
Input flexibility
Output capability
Functionality
Technical approach
Validation
Audience
Customer support
Price
Usage

Details, including contact information for the respective tools, are given in Table 1. The definitions of the items in the evaluation matrix are given in Table 4.

Five tools are subsequently selected for conducting detailed evaluation of their use in the context of early design support. These are (1) Green Building Studio, (2) eQUEST, (3) Energy Scheming, (4) Ecotect, and (5) TAS. These tools are selected because they are relatively known and considered to hold particular promise for use in schematic design. This selection may be regarded as representative of the broad categories of tools that exist in industry. The same information contained in Table 1 has been extracted and tabulated for these five tools for convenient comparison in Table 2.

Evaluation of Selected Tools for the Early Design Phase

The evaluation of the five selected tools is structured to address the following themes in computational design modeling and analysis:

- Usability
  - System requirements
  - Interoperability with other tools, import/export capabilities
  - User interface
  - Learning and training time required
  - Effort required in updating model/conducting parametric studies
  - Processing time
- Functionality
  - Comprehensiveness of geometric and system modeling
  - Types of energy calculations (e.g., load estimation, HVAC systems performance, etc.)
  - Types of data analysis and presentation
  - Availability of other environmental domain simulations (e.g., lighting)
- Reliability
  - Consistency of results
  - Accuracy of results
- Prevalence
  - Compliance with industry standards
  - Documentation
  - User support
  - Pricing and licensing

The exercise involves two major tasks: (1) development of a comprehensive classification schema for comparing the five selected tools, and (2) application and experimental testing of the tools in "simulated" architectural practice scenarios conducted by graduate students and selected practicing architects under controlled conditions.

A detailed matrix of features is developed to enable a comprehensive comparison of the five selected tools according to the major themes stated above, and represented by the following specific criteria:

1. System
2. Extension
3. Functionality
4. User

Sustainability Performance Simulation Tools for Building Design. Table 1 Summary of a survey of existing energy modeling tools

	ApacheSim (part of VE of IES)	BDA 3.1 (Building design advisor)	BSim	COMFIE v3.0
User interface	Graphical user interface	Graphical schematic editor, building browser and decision desktop	SimView graphical user interface and model editor	Graphical user interface (PLEIADES)
CAD interface	Yes	No	Yes	No
Ease of use	2 days of training is recommended for the basic modules	Easy (according to the developer)	Courses available	Easy (according to the developer)
Manuals		User's guide, online help	User's guide	User's manual
Computer Platform	Windows 2000/XP	Windows 95/98/NT/2000	Windows NT/2000/XP/Vista	PC or Macintosh
Expertise required	2 days of training is recommended for the basic modules, with additional courses available for specific applications	Knowledge of Windows applications	General knowledge of building design and how buildings behave thermally	High level of computer literacy not required
Input Flexibility	Certain energy systems such as PCM and roof ponds not covered	Complex 3-D geometry and sloping roofs not covered	Unlimited rooms and zones	Readable and structured input file generated by Pleiades user interface
Output capability	Presents a wide range of data outputs in tabular and graphical form. All reportage can be copied into word processing and spreadsheet packages	User-selected output parameters displayed in graphic form, including 2-D and 3-D distributions	Tabular or graphic output of any of the calculated parameters on hourly, weekly, monthly, or periodical basis, numeric output is also available	Heating and cooling load, system sizing information, hourly indoor temperature profile and temperature histogram
Functionality	Hourly simulation of solar shading and penetration (SunCast) HVAC systems and control (Apache HVAC) natural ventilation and mixed mode systems (MacroFlo)	Daylighting analysis and electric lighting computation, thermal and energy analysis, comparison of multiple design alternatives	Simultaneous thermal and moisture simulation, dynamic solar and shadow simulation, daylighting calculation, building integrated PV system calculation	Heating and cooling load calculation, system sizing, hourly temperature profile, comfort evaluation

Technical approach	Based on first-principles models of heat transfer and is driven by real weather data	Simplified daylighting analysis and electric lighting computation, DOE-2.1E energy simulation engine	Finite time step, finite difference on building envelope	Finite volume method for building simulation, simplified mechanical system modeling
Validation	Independent testing by other companies and institutions shows good results Development is supported by current research	DOE-2.1E is subject to BESTEST validation procedure	Thermal simulation core has been validated in the IEA Task 12/ Annex 21	Empirical validation and inter-model comparison with ESP-r
Audience	Mechanical building services engineers	Architects and engineers, in early design phases	Engineers, researchers, and students	Architectural engineers, energy consultants, architects
Customer support	Available from the developer	Available from LBNL	Available from the developer	Available from the developer, users' club
Price	Depends on retailers	Free	2,680 EUR annual for up to 5 users/ PCs	Approximately $1,000 for new installations
Usage	Many throughout Europe	800+ as of 09/2010	650 licenses (most of which in Denmark and Germany)	100+
Contact	Don McLean IES Ltd. Helix Building, West of Scotland Science Park Kelvin Campus Glasgow G20 0SP UK Tel: +44 (141) 945 8500 Fax: +44 (141) 945 8501 E-mail: don.mclean@iesve.com Web: http://www.iesve.com	Konstantinos Papamichael Lawrence Berkeley National Laboratory Mail Stop 90-3111 1 Cyclotron Road Berkeley, California 94720 Tel: (510) 486-6854 Fax: (510) 486-4089 E-mail: MAJohnson@lbl.gov Web: http://gaia.lbl.gov/BDA	Kim B. Wittchen Aalborg university Dr. Neergaards Vej 15 Hoersholm DK-2970 Denmark Tel: +45 (45) 86 5533 Fax: +45 (42) 86 7535 E-mail: bsim-support@sbi.dk Web: http://www.bsim.dk	Bruno Peuportier 60, Bd St Michel 75272 Paris Cedex 0 France Tel: +33 1 40 51 9151 Fax: +33 1 46 34 24 91 E-mail: peuportier@cenerg.ensmp.fr Web: http://www-cenerg.ensmp.fr/english/themes
	DEROB-LTH v2.0	*DOE-2.1E*	*Autodesk ECOTECT Analysis*	*EnerCAD 2010*
User interface	User friendly graphical interface	Text input file	Intuitive 3D modeling interface	Graphical interface
Cad interface	No	No	Yes	No

Sustainability Performance Simulation Tools for Building Design. Table 1 (Continued)

	ApacheSim (part of VE of IES)	BDA 3.1 (Building design advisor)	BSim	COMFIE v3.0
Ease of use	Easy (according to the developer)	Recommend 3 days of formal training in basic and advanced DOE-2 use	Easy (according to the developer)	Input assistants make the program easy to use. User interface structured to facilitate error-free inputs
Manuals	NA	User's manual, reference manual, engineer's manual	Tutorials, online help	User's guide
Computer Platform	Windows 95/MS Windows NT	Windows 95/98/ME/2000/NT, UNIX, DOS, VMS	Windows 2000/XP/Vista/7 or Macintosh	Compatible with multi-platform of WIN, MAC-OS, Linux
Expertise required	An overall knowledge of the influence of different design parameters on the thermal behavior of buildings	3-day training recommended	CAD and environmental design experience useful but not essential	None required
Input flexibility	Up to 8 rooms	Up to 200 zones, 512 interior walls, fixed system configurations	Can deal with highly complex 3D models. BIM integration provided	EnerCAD offers default values for all input and extensive building material, window, and wall libraries
Output capability	Simple diagrams for space temperatures, space heating and cooling demand and solar parameters, diagrams for the distribution of the comfort indices PMV and PPD for one space	Numerical output of input verification report, performance summaries, design day summaries and hourly report for building thermal performance, energy consumption, and cost	Graphic output of thermal, lighting, acoustic and cost results, export to RADIANCE, EnergyPlus, ESP-r etc.	Table of monthly values, annual heat demand, monthly histogram, flux diagram
Functionality	Hourly calculation of temperature and comfort level, detailed window and shading modeling, flexible modeling of building	Numerical output of detailed, hourly, whole building energy analysis of multiple zones in buildings of complex design, operational energy cost calculation, daylighting analysis included	Hourly simulation of lighting, thermal and acoustic performance, discomfort level, resource management, daylighting analysis included	Monthly calculation of cooling and heating load, U-value calculator, shading calculator, window calculator
Technical approach	RC-network building thermal model, simplified mechanical system modeling	Hour-by-hour, response factors for walls, weighting factors for zones, rectilinear surface model for daylighting	CIBSE Admittance Method for load calculation, hour-by-hour building, and system thermal performance simulation	Monthly heat balance method

Validation	NA	Subject to BESTEST validation procedure	NA	Based on Swiss "recommendation SIA 380/1" edition 2009 and the European "Thermal performance of buildings EN 832"
Audience	Students, researchers, and energy consultants	Architects, engineers, energy consultants, researchers	Architects, engineers, environmental consultants	Architects and building engineers
Customer support	Support maintained from Lund Institute of Technology, Lund University	LBNL help line, commercial sources	Support forum maintained by Autodesk Support	Support provided by EnerCAD 2010 Web site
Price	500 EUR – Research License 2000 EUR – Commercial License	$300–$2,000	Provided from local re-sellers	CHF 760 Pro version CHF 50 Educational version
Usage	150	800 user organizations in USA. 200 user organizations internationally	NA	500+
Contact	Lund Institute of Technology, Lund University, Box 118, Lund, 221 00, Sweden. Tel: +46 (46) 222 9662 Fax: +46 (46) 222 4719 E-mail: Maria.Wall@Ebd.Lth.Se Web: http://www.derob.se	Fred Winkelmann Lawrence Berkeley National Laboratory, Mail Stop 90-3147, 1 Cyclotron Road, Berkeley, California 94720. Tel: (510) 486–5711, Fax: (510) 486-4089.E-mail: FCWinkelmann@lbl.gov Web: http://simulationresearch.lbl.gov	Autodesk Ecotect Analysis and Green Building Studio Services & Support Web: http://usa.autodesk.com/adsk/servlet/ps/index?siteID=12311 2&id=13740368&linkID=13734 494	CUEPE University of Geneva Battelle bat. A 7, rte de Drize Carouge/Gevera, 1227 Switzerland Fax: +41 (22) 705 96 39 E-mail: info@enercad.ch Web: http://www.enercad.ch
	Energy-10 v1.8	*Energy Scheming v3*	*ENER-WIN Version e9*	*eQUEST*
User interface	Menu-driven input system	Graphical interface	Graphical interface (zone sketch interface)	Graphical interface, schematic design wizard, design development wizard
CAD interface	No	Yes	No	Yes
Ease of use	Autobuild feature makes the tool easy to use	Predefined building elements make the tool easy to use	Easy to use	Knowledge-based default values make the tool easy to use
Manuals	User's manual and help system	User's manual	Users manual/Web-documentation	Tutorials, online help

Sustainability Performance Simulation Tools for Building Design. Table 1 (Continued)

	ApacheSim (part of VE of IES)	BDA 3.1 (Building design advisor)	BSim	COMFIE v3.0
Computer platform	Windows 3.1/95/98/2000/NT	Macintosh or Windows	Windows 95/98/NT/ME/2000/XP/ Vista and 7	Windows 95/98/ME/NT/2000/XP/ Vista
Expertise required	Moderate level of computer literacy required, 2 days of training advised	Understanding of basic concepts of energy design Familiarity with the Mac interface is helpful	Experience with Windows applications. Knowledge of building thermal properties and energy concepts	Understanding of basic concepts of building and HVAC system design
Input flexibility	Building size less than 10,000 sf, up to 2 zones, 10 surfaces per zone, limited HVAC system types	Single zone, do not have HVAC systems, do not intend to be a building simulation program	25 zones per floor, up to 98 zones in total, 200 walls and 400 surfaces, 42 building types from ASHRAE	Inputs can be provided at three levels: schematic design, design development, and detailed interface
Output capability	Comparison of various EEMs between reference and base case building, annual energy cost, cost-effectiveness ranking of EEMs	Graphic and numeric reports showing heat gain and loss by hour for each of the calculation days	Annual utility and energy costs with peaks, thermal comfort analysis, life-cycle cost summary	Output of monthly and annual energy consumption by end use, graphic comparison of alternative designs, detailed numeric load, system, plant and economics reports
Functionality	Automatic generation of base cases and energy-efficient alternative case, rank-ordering of EEMs, annual operation cost calculation, daylighting analysis included Photovoltaic Module, Solar Domestic Hot Water Module, and ASHRAE Material Library are added to v1.8	Loads analysis for 24 h for each of 4 seasonal evaluation days, daylighting analysis included	Peak cooling and heating load calculation and zone sizing, hourly calculation of energy performance, Simplified HVAC system simulation	Hourly simulation of thermal and energy performance as well as energy cost, parametric runs, comparison of alternative designs
Technical approach	CNE thermal network thermal simulation engine, 15-min time step, rectilinear surface model for daylighting (split flux method)	Hourly calculation of 4 evaluation days	Transient modeling based on sol-air temperature, time lag, decrement factor, ETD; zone loads and temperatures based on a heat balance methodology; and daylighting algorithms based on a modified Daylight Factor methodology	DOE-2.2 simulation engine

Validation	Subject to BESTEST validation procedure	NA	Empirical validation	DOE-2 is subject to BESTEST validation procedure
Audience	Building designers, HVAC engineers, utility companies	Architectural professionals, students, and building designers	Architects, engineers, energy analyst, building inspectors, student	Building designers, operators, owners, energy/LEED consultants
Customer support	Commercially available from SBIC	Support maintained from Oikos (Oikos.com)	Available from the developer	Available from Doe2.com
Price	$375 ($315 SBIC Members)	$250	$249 for professional license	Free
Usage	3,200+ as of 09/2010	600+	Estimated to be in low 100s	# of full program downloads is approximately 10,000 per annum
Contact	Sustainable Buildings Industry Council Suite 240 1112 16th Street NW Washington D.C. 20036 U.S. Tel: (202) 628-7400 ext 210 Fax: (202) 393-5043 Email: SBIC@SBICouncil.org Web: http://sbicouncil.org/displayc ommon.cfm?an=1&subarticlenbr=110	G. Z. Brown Energy Studies in Buildings Laboratory Department of Architecture University of Oregon Eugene, Oregon 97403 Tel: (541) 346-5647 Fax: (541) 346-3626 Email: GZBrown@aaa.uoregon.edu	Larry O. Degelman Degelman Engineering Group, Inc. 2206 Quail Run College Station, Texas 77845 U. S. Email: ldegelman@suddenlink.net Web: http://pages.suddenlink.net/en erwin	James J. Hirsch & Associates 12185 Presilla Road Camarillo CA 93012-9243 Email: Jeff.Hirsch@doe2.com Web: www.doe2.com
	Green Building Studio	*HAP*	*PowerDOE*	*RIUSKA*
User interface	Web-based	Explorer style graphical user interface	Graphical interface	Windows-based graphical interface
CAD interface	Yes, integration to BIM tools	No	Yes	Yes, integration with BIM tools
Ease of use	Easy to use focused on early design phases	Requires training or extensive use to be proficient	Training is highly recommended by developer	Default data libraries
Manuals	Online help, tutorials	User's manual and reference guide, online help	Quick start guide, tutorial, online help	
Computer Platform	Windows and MAC-OS	Windows 98/NT/2000/XP/Vista Windows 7	DOS, UNIX, Windows May not operate properly with more recent versions such as XP and Vista	Windows 2000/XP/Vista/7
Expertise required	Knowledge of BIM tools and basic understanding of environmental performance outputs	General knowledge of HVAC engineering principles	Training is highly recommended	Engineering background required to analyze calculation results.

Sustainability Performance Simulation Tools for Building Design. Table 1 (Continued)

	ApacheSim (part of VE of IES)	BDA 3.1 (Building design advisor)	BSim	COMFIE v3.0
Input flexibility	Unlimited number of thermal zones at the expense of increased computation time	100 plants, 250 systems, 2,500 spaces, unlimited building elements fixed system configurations		The flexibility associated with DOE-2.1E
Output capability	Wide range of environmental performance outputs: building energy and carbon emission reporting, daylighting, water usage and costs, ENERGY STAR scoring, natural ventilation potential	Graphical and numerical output of design reports and hourly, daily, monthly, or annual simulation reports	Graphical and numeric outputs of schedules, peak loads, monthly and annual energy consumption	Numerical output of hourly and annual heating and cooling loads, energy consumption and temperature profile
Functionality	Hourly energy performance simulation using DOE-2 engine. Determines appropriate defaults based on building type and location (majority of defaults are ASHRAE 90.1-2004 compliant)	Load calculation, system sizing, hourly thermal and energy performance simulation, operating energy cost calculation	Hourly simulation of thermal and energy performance	Hourly calculation of building and system energy performance, can be used for life-cycle data management
Technical approach	DOE-2 thermal simulation engine	ASHRAE-endorsed transfer function methodology for load calculation, hour-by-hour thermal and energy simulation	DOE-2.2 simulation engine	DOE-2.1E thermal simulation engine
Validation	DOE-2 is subject to BESTEST validation procedure	Comparison studies with DOE-2.1 yielded good correlation	DOE-2 is subject to BESTEST validation procedure	DOE-2 is subject to BESTEST validation procedure
Audience	Architects and designers	Consulting engineers, design/build contractors, HVAC contractors, facility engineers	engineers, energy consultants, and utility staff	architectural engineers
Customer support	Provided by Autodesk	Carrier factory support and training available	Available from the developer	–

Price	$745 Single user annual subscription $4,995 ten user annual subscription	$1,195 for first year and $240 thereafter	$278 for non-expiration license	–
Usage	unknown	Approximately 5,000 worldwide as of 07/2002	Unknown	About 20 in Finland
Contact	Autodesk Green Building Studio Web: http://usa.autodesk.com/adsk/servlet/pc/index?id=11179508&siteID=123112	Carrier Corporation Bldg TR-4 P.O. Box 4808 Syracuse, New York 13221 Tel: (315) 432-6838 Fax: (315) 432-6844 Email: software.systems@carrier.utc.com Web: http://www.carrier-commercial.com/software	James J. Hirsch & Associates Email: Jeff.Hirsch@doe2.com Web: www.doe2.com	Tuomas Laine Olof Granlund Oy Malminkaari 21 P.O. Box 59 Helsinki, FIN-00701 Tel: +358 (9) 351031 Fax: +358 (9) 35103421 Email: Tuomas.Laine@granlund.fi
	TAS 9.1.4.2	*TRACE 700*	*VisualDOE 4.0*	*Energy Plus v6.0*
User interface	Windows-based graphical interface	Windows-based graphical interface, multiple views, drag and drop load assignments	Graphical interface	No "user friendly" graphical interface
CAD interface	Yes	Yes, integration with BIM tools	Yes	No
Ease of use	Qualified engineer or architect, No training courses are required	Formal training recommended for new users	Not as easy as eQUEST or Energy-10 (According to 21CR)	Text input may make it difficult to use compared to graphical interfaces
Manuals	Users manual	Engineer's manual, online help, modeling guide	User's manual, online help system	Well-documented input/output and engineering reference
Computer Platform	Windows NT	Windows 95/98/ME/NT/2000/ME/XP/7	Windows 95/98/NT/ME/2000/XP/7	Windows XP/Vista/7, Mac OS and Linux
Expertise required	General knowledge of architectural engineering and building design	General knowledge of HVAC engineering principles	Basic experience with Windows software. Familiarity with building systems is recommended. One to two days of training also recommended	High level of computer literacy not required, engineering background is helpful for analysis portions
Input Flexibility	Unlimited number of zones, rooms, and surfaces	Unlimited rooms, systems, and building elements, fixed system configurations	Up to 1,024 zones and 256 systems, analysis of up to 99 alternatives	Unlimited number of zones and surfaces, uses a simple ASCII input file

Sustainability Performance Simulation Tools for Building Design. Table 1 (Continued)

	ApacheSim (part of VE of IES)	BDA 3.1 (Building design advisor)	BSim	COMFIE v3.0
Output capability	Numerical and graphical output of any simulation parameter over any period of time	Graphical and numerical output of design parameters, hourly building temperature profiles and energy consumption, comparison of various alternatives, predefined reports	Graphical comparison of design alternatives or selected parameters, standard DOE-2.1E numeric output, LEED style end-use report Life cycle cost analysis of design alternatives	Has a number of ASCII output files which can be readily adapted into spreadsheet form for further analysis, reporting of EER, SEER, and IEER for DX cooling coils, enhanced SQLite output.
Functionality	System sizing, Hourly simulation of heating and cooling demand, CFD, daylighting	Load calculation, system sizing, comparison of up to 4 system design alternatives through hour-by-hour simulation, life-cycle cost calculation, daylighting analysis included, ASHRAE 90.1-2004 analysis	Hour-by-hour simulation of thermal and energy performance as well as energy cost, daylighting analysis included, comparison of alternative designs, 95% of DOE-2.1E's functions	Innovative simulation capabilities including steps of less than an hour, modular systems simulation modules integrated with a heat balance–based zone simulation. Multizone airflow, electric power simulation including fuel cells and other distribution systems, water management systems, Model library for DOE reference buildings (including a 130-zone hospital baseline). Life-cycle costing dataset with US regional fuel escalation factors, functionality of running multiple simulations simultaneously, movable and transparent insulation (TIM) modeling, Ecoroof model, separate sizing factors for heating and cooling

Technical approach	Hourly simulation of dynamic building and system performance	Choose from 7 different ASHRAE load methodologies, Hourly calculation available, rectilinear surface model for daylighting	DOE-2.1E simulation engine	Energy Plus simulation engine (BLAST + DOE-2.1E), significant increase with v6.0 (up to 25–40% execution time reduction), surface heat transfer convection coefficient options for adaptive models
Validation	Empirical validation using IEA test data, EPC and Part L, BEEM, ASHRAE 140-1	Tested according to ASHRAE Standard 140	DOE-2 is subject to BESTEST validation procedure	Tested and validated against the IEA BESTEST building load and HVAC tests
Audience	Building services engineers and architects	Engineers, architects, energy consultants, and utility companies	Mechanical/electrical/energy engineers and architects	Mechanical energy and architectural engineers
Customer support	Available from the developer	Free technical support from Trane factory, training available	Available from Architectural Energy Corporation	Provided by US DOE http://apps1.eere.energy.gov/buildings/energyplus/
Price	1,600+	$1,995 for single license, $3,990 for site/LAN license	$1,250 single commercial $650 single educational	free
Usage	250 user sites	Approximately 1,200 worldwide as of 05/2001	1,000+ as of 08/2002	85,000+ downloads since April 2001
Contact	Alan M. Jones EDSL Ltd 13/14 Cofferidge Close Stony Stratford Milton Keynes, Mk11 1BY United Kingdom +44 (1908) 261 461 +44 (1908) 566 553 Email: info@edsl.net Web: http://www.edsl.net/	The Trane Company 3600 Pammel Creek Road La Crosse, Wisconsin 54601 Tel: (608) 787-3926 Fax: (608) 787-3005 Email: CDSHelp@trane.com Web: http://www.trane.com/commercial/software	Architectural Energy Corporation 142 Minna Street, 2nd Floor San Francisco, CA 94105 U.S. Tel: (415) 957-1977 Fax: (415) 957-1381 Email: vdoesupport@archenergy.com Web: http://www.archenergy.com/products/visualdoe/	U.S. Department of Energy EE-2J Building Technologies 1000 Independence Avenue, SW Washington D.C. 20585-0121 U.S. Tel: +1 (202) 586-2344 E-mail: Drury.Crawley@ee.doe.gov Web: http://www.energyplus.gov

Sustainability Performance Simulation Tools for Building Design. Table 2 List of selected energy modeling tools for experimental evaluation

	ECOTECT	TAS	Green building studio	eQUEST	Energy scheming
User interface	Intuitive 3D modeling interface	Windows-based graphical interface	Web-based	Graphical interface, schematic design wizard, design development wizard	Graphical interface
Cad interface	Yes	Yes	Yes	Yes	No
Ease of use	Easy (according to the developer)	Easy to use, No training courses are required		Easy (according to the developer)	Predefined building elements make the tool easy to use
Manuals	Tutorials, online help	Users manual	Online help, tutorials	Tutorials, online help	User's manual
Computer platform	Windows 95/98/NT/2000/XP or Macintosh	Windows NT		Windows 95/98/ME/NT/2000/XP	Macintosh or Windows
Expertise required	CAD and environmental design experience useful but not essential	General knowledge of architectural engineering and building design		Understanding of basic concepts of building and HVAC system design	Understanding of basic concepts of energy design
Input Flexibility	Can deal with highly complex 3D models	Unlimited number of zones, rooms, and surfaces		Only 3 floors could be defined (according to Charli_and_Mahabir_Overview_simulation_model.ppt)	Single zone, do not have HVAC systems, do not intend to be a building simulation program
Output capability	Graphic output of thermal, lighting, acoustic and cost results, export to RADIANCE, EnergyPlus, ESP-r etc.	Numerical and graphical output of any simulation parameter over any period of time		Graphic output of monthly and annual energy consumption by end use, graphic comparison of alternative designs, detailed numeric load, system, plant and economics reports	Graphic and numeric reports showing heat gain and loss by hour for each of the calculation days
Functionality	Hourly simulation of lighting, thermal and acoustic performance, discomfort level, resource management, daylighting analysis included	System sizing, hour-by-hour simulation of heating and cooling demand, CFD, daylighting		Hour-by-hour simulation of thermal and energy performance as well as energy cost, parametric runs, comparison of alternative designs	Loads analysis for 24 h for each of 4 seasonal evaluation days, daylighting analysis included

Sustainability Performance Simulation Tools for Building Design. Table 2 (Continued)

	ECOTECT	TAS	Green building studio	eQUEST	Energy scheming
Technical approach	CIBSE Admittance Method for load calculation, hour-by-hour building and system thermal performance simulation	Hour-by-hour simulation of dynamic building and system performance	DOE-2 thermal simulation engine	DOE-2.2 simulation engine	Hourly calculation of four evaluation days
Validation	Undergoing	Empirical validation using IEA test data	DOE-2 is subject to BESTEST validation procedure	DOE-2 is subject to BESTEST validation procedure	
Audience	Architects, engineers, environmental consultants	Building services engineers and architects		Architects, architectural engineers	Architects
Customer support	Support forum maintained by the developer	Available from the developer	Available from GeoPraxis, Inc.		
Price	$650 for first professional license, $350 for education and $90 for student	UK$1,600+	Free	Free	$250
Usage	2,000+ as of 09/2002	200+	Unknown	Unknown	600+ as of 03/1999
Contact	Square One Research Pty Ltd c/o Center for Research in the Built Environment Cardiff University, Bute Building, Cardiff, Wales CF10 2NB, UK Tel: +44 (29) 2087 5977 Fax: +44 (29) 2087 4623 Email: sales@squ1.com Web: http://www.squ1.com	Alan M. Jones EDSL Ltd 13/14 Cofferidge Close Stony Stratford Milton Keynes, Mk11 1BY United Kingdom +44 (1908) 261 461 +44 (1908) 566 553 Email: info_edsl@csi.com Web: http://ourworld.compuserve.com/homepages/edsl	John F. Kennedy GeoPraxis, Inc. Tel: 707.766.7010 Fax: 707.766.7014 Email: jfk@geopraxis.com Web: www.geopraxis.com	James J. Hirsch & Associates Email: Jeff.Hirsch@doe2.com Web: www.doe2.com	G. Z. Brown Energy Studies in Buildings Laboratory Department of Architecture University of Oregon Eugene, Oregon 97403 Tel: (541) 346-5647 Fax: (541) 346-3626 Email: GZBrown@aaa.uoregon.edu

5. Modeling
   (a) Project information
   (b) Building modeling
   (c) HVAC modeling
6. Result output

Detailed description of these features and the definitions of the items in the evaluation matrix are given in Tables 3 and 4.

Sustainability Performance Simulation Tools for Building Design. Table 3 Selected energy modeling tools: Matrix of features

I. System					
Operating platform					
Windows	Yes	Yes	Yes	Yes	Yes (emulated Mac)
Mac OS	No	No	Yes	No	Yes
Unit system	SI and English	SI	SI and English	English	SI and English
Energy design guidance	No	No	No	Yes (general guidance available in tutorial)	Yes (specific advice in context of the building design, in text or audio format)
Built-in library[a]					
Weather data	Ye	Yes	Yes	Yes	Yes
Material	Yes	Yes	Yes	Yes	Yes
Construction	Yes	Yes	Yes	Yes	Yes
Schedule	No	Yes	Yes	Yes	Yes
Internal heat gain	No	Yes	Yes	Yes	Yes
Infiltration	No	Yes	Yes	Yes	Yes
HVAC system type	No	No (available in separate plug-in)	Yes	Yes	No
HVAC equipment	No	Yes	Yes	Yes	No
Simulation application					
Stand-alone	Yes	Yes	No	Yes	Yes
Web-powered	No	No	Yes (via Internet)	No	No
Program stability	Moderate (Exception errors when working with multiple projects during single session. Program should be restarted when closing one project and opening another project)	Moderate (120MB file size limitation. Program unstable when a larger number of reports are requested)	Stable	Crash occasionally	Crash occasionally (beta version evaluated)

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

I. System					
Weather file	Library and user definable	Library and user definable	According to zip code	According to geographical location (can be downloaded from doe-2.com ftp site by eQUEST)	No separate weather file, weather data is specified in input interface
Types of weather files	.wea (weather tool data)	.twd (TAS weather database)	Unsure	.bin file	N/A
History tracking					
Undo/redo	Yes (single state undo/redo only)	Yes	No (available in CAD tool)	No	No
Error logging	Yes	Yes	Yes (runtime error message)	Yes (separate error log file)	Yes (runtime error message)
II. Extension					
Interoperability					
IFC compliance	No	No	No	No	No
File exchange with other energy simulation tools	Yes (export of EnergyPlus, ESP-r file)	No	Yes (export of.inp and gbxml file, import of gbxml file is not visible to the user)	Yes (import of.inp file)	Yes (export of. doe2 file)
File exchange with CAD tools	Yes (Autodesk Architectural Desktop and 3D studio file)	No	Yes (.dwg from Autodesk Architectural Desktop,.pne from ArchiCAD,.rvt from Revit, unsure from Autodesk Building System All CAD information is imported into GBS through SOAP and a gbXML file)	No	No
Drawing data input					
Import as underlay	Yes (AutoCad DXF, ASCII model, 3D studio, Stereo Lithography, Radiant Scene, HPGL plot, Ray, Analysis Grid files)	Yes (AutoCAD. dwg and dxf files)	No	Yes (AutoCAD.dwg files)	No (copy and paste drawings from other programs as underlay)

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

II. Extension					
Building element import	Yes (AutoCad DXF, ASCII model, 3D studio, Stereo Lithography, Radiant Scene, HPGL plot, Ray, Analysis Grid files) – Element information not included	No	Yes	No	No
III. Functionality					
Technical approach	CIBSE admittance method	TBD (Dynamic Simulation)	DOE-2.2 simulation engine	DOE 2.2 simulation engine	Hourly calculation of building load for 4 evaluation days
Types of energy calculation					
Building load calculation	Yes	Yes	Not visible in GBS result output. Available in gbxml file exported from GBS	Not visible in eQUEST graphic result output. Available in detailed simulation output file	Yes
Building energy simulation	No	No	Yes	Yes	No
Parametric operation					
Single run/single input and output	Yes	Yes	Yes	Yes	Yes
Batch processing	No	Yes	No	Yes	No
Code compliance	Yes (UK Part-L)	Yes (UK Part-L)	No	Yes	No
Cost estimation	Yes (material cost and resource consumptions, energy cost not included)	No	Yes (annual energy cost and lifecycle operating cost)	Yes (monthly and annual energy cost, lifecycle cost)	No
IV. User					
Documentation					
Tutorial/manuals/wizard	Tutorial, some background of thermal analysis in help file and in html file and example/tutorial files	Separate help file and video tutorial	Tutorial for installation and basic usage in pdf and video format	Tutorial in pdf format, schematic design and design development wizards	User's manual in hard copy and pdf format
Engineering documentation	No	No	No	Yes (combined in tutorial)	Yes (combined in user's manual)

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

IV. User					
Help function	Yes (help menu, help topic, FAQ, balloon help)	No (in manager, menu list only in modeler in simulator)	Yes (help menu)	Yes (help menu and on-screen help)	No
User support	Yes (homepages, helpdesk, forum, online courses)	Yes (helpdesk, training)	Yes (inquiry and issues submission through Web site)	Unsure	Yes (by phone or email)
File save interval	Anytime	Anytime	Anytime	Anytime with the exception when the building creation wizard window is open	Anytime with the exception of when a specification window is opened, in which case the user is prompted to close it
Navigation between windows	Flexible random	Flexible random	Flexible random	Flexible random	Flexible random
Clarity of menu and tool bars	Yes	Yes	Yes	Yes	Yes
Model view	Yes (2D and 3D)	Yes (2D and 3D)	No (view in VRML in external application)	Yes (2D and 3D)	Yes (2D)
Model display	Wireframe, Shaded, OpenGL and VRML	Wireframe and Shaded	VRML	Shaded	As pasted or drawn
Expertise required	General knowledge about building energy simulation and thermal analysis.	General knowledge about building energy simulation and thermal analysis.	Experience of 3D CAD tool (Autodesk Architectural Desktop, ArchiCAD, Revit, Autodesk Building System)	General knowledge about building energy simulation and thermal analysis. DOE-2 experience required in detailed data edit mode	General knowledge about building thermal analysis
V. Modeling					
Zone management	By zone management dialog	By zones and zone groups	By space list table	By activity area allocation, no information about the specific location in the building in schematic design wizard	By occupancy, lighting, and equipment zones

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

a. Project information					
Building type definition	Yes (Domestic dwelling, commercial residential, office/ shop/assembly, industrial or storage, others) only used in the UK Part-L analysis	No (for project labeling only)	Yes (see appendix, links to default values)	Yes (see appendix, links to default values)	Yes (links to default values)
Space type definition	No (conventionally specified in zone management dialog as zone name)	No	Yes (see appendix, links to default values)	Yes (see appendix, links to default values)	No
b. Building modeling					
Geometry					
Space composition					
Buildup by spaces	Yes	Yes	No (done in CAD tool)	Yes	Yes
Subdivision of floor plate	Yes	Yes	No (done in CAD tool)	Yes	Yes
Direct drawing input					
Primitive shapes	No	No	No (done in CAD tool)	No	No
Extrusion based on closed curve	Yes	Yes	No (done in CAD tool)	Yes	No
Surfaces	Yes	No	No (done in CAD tool)	No	Yes
Building element definition	Yes (void, roof, floor, ceiling, wall, partition, window, panel, door, point, speaker, light, appliance, solar collector, camera, line)	Yes (floor, building element and window)	No (Defined in the CAD input file)	No	Yes
Different heights within floor	Yes	Yes	Yes	Not available in wizard data edit mode, flexible in detailed data edit mode	Yes
Sloped roof	Yes	Yes	No (done in CAD tool)	Yes	Yes
Sloped floor	Yes	No	No (done in CAD tool)	No (except in detailed data edit mode)	No

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Building orientation	Yes	Yes	Yes	Yes	Orientation of elevations and roof surfaces available
Accessible coordinate data	Yes (Cartesian coordinate and polar coordinate)	No	Not shown in the user interface, available in CAD tool and gbxml file exported from GBS	Yes	No
Snap function	Yes (snap to grid or object)	Yes (snap to overlay only)	No (available in CAD tool)	Yes (to overlay and grid)	No
Modification	Yes (transform(move, rotate, scale, mirror, extrude, revolve, spin), morph, link/unlink, group/ungroup)	Yes (delete, change alignment)	No (done in CAD tool)	Yes	Yes
Geometry checking	Yes	No	Yes	Unsure	No
Building construction					
Material	Selectable from the library and user definable	Selectable from the library and user definable	Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user.	Selectable from the library, not editable and definable except in detailed data edit mode	Selectable from the library and user definable
Layer	User definable	User definable	Not visible, editable and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user	Selectable from the library, not editable and definable except in detailed data edit mode	Selectable from the library and user definable

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Construction	Selectable from the library and user definable	Selectable from the library and user definable	Not visible, editable, and definable by user. Visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user	Selectable from the library, not editable and definable except in detailed data edit mode	Selectable from the library and user definable
Shades	User definable	User definable	Not visible, editable. and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user	Selectable from the library, editable but not definable except in detailed data edit mode	Selectable from the library and user definable
Default values	No	No	Yes	Yes	Yes
Recommendation	No	No	Yes (according to building type and geographical location)	Yes (according to building type)	Yes (according to building type)
Internal loads					
Occupant					
Load					
Density	Yes (user definable)	Yes (user definable)	No	Yes (editable)	Yes (selectable from the library and user definable)
Total number of occupants	Yes	Yes	Yes (Not visible, editable, and definable by user except in ABS. Visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes	No

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Schedule	Yes (User definable)	Yes (Selectable from the library and user definable)	Yes (Not visible, editable and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (selectable from the library, not editable, and definable except in detailed data edit mode)	Yes (user editable, occupied/ unoccupied only, one schedule per day for all occupancy zones)
Lighting					
Load					
Density	Yes (User definable combined with Equipment Load)	Yes (User definable)	Yes (Not visible, editable, and definable by user. Visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable)	Yes(selectable from the library and user definable)
Individual appliance	Yes (User definable)	Yes	Yes (Not visible, editable and definable by user except in ABS)	No	No
Schedule	Yes (user definable)	Yes (Selectable from the library and user definable)	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (selectable from the library, not editable, and definable except in detailed data edit mode)	Yes (user editable, on/ off only, one schedule per day for all lighting zones

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Equipment					
Load					
Density	Yes (User definable combined with Lighting Load)	Yes (User definable)	Yes (Not visible, editable, and definable by user. Visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable)	Yes (selectable from the library and user definable)
Individual appliance	Yes	Yes	Yes (Not visible, editable, and definable by user except in ABS)	No	Yes (selectable from the library and user definable)
Schedule	Yes (User definable)	Yes (Selectable from the library and user definable)	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (Selectable from the library, not editable, and definable except in detailed data edit mode)	Yes (user editable, on/off only, one schedule per day for all equipment zones)
Default values	No	No	Yes	Yes	Yes
Recommendation	No	No	Yes (according to building type, location, floor area, and ratio of surface to floor area)	Yes (according to building type and activity area type)	Yes (according to building type)

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Infiltration					
Rate	Yes (User definable)	Yes (User definable)	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable)	Yes (selectable from the library and user definable)
Schedule	Yes (User definable)	Yes (Selectable from the library and user definable)	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes	Yes (follows occupant schedule)
Default values	No	No	Yes	Yes	Yes
Recommendation	No	No	Yes (according to building type)	Yes	Unavailable in input process, available in design guidance advice
Utility					
Rate	Yes (for equipment only)	No	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (selectable from the library, and user definable)	No

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

b. Building modeling					
Schedule	Yes (User definable)	No	Yes (Not visible, editable and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (selectable from the library, and user definable)	No
Default values	No	No	Yes	Yes (for California only)	No
Recommendation	No	No	Yes (according to building location)	Yes (according to climate zone and estimated peak electrical demand)	No
c. HVAC modeling					
Thermostat setpoint	Yes	Yes	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable)	Yes
HVAC zoning	Yes (multizones)	Yes (multizones)	Yes (multizones)	Yes (multizones)	No
Relationship between HVAC zone and building space	HVAC zone same as the building space	One HVAC zone can have multiple spaces	HVAC zone same as the building space	HVAC zone different from building space	N/A
Zone grouping	No	Yes	No	Yes	No

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

c. HVAC modeling					
HVAC schedule	Yes (Fixed on/off timing for entire year)	Yes	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user.)	Yes (editable)	No
Default values	No	No	Yes	Yes	No
Recommendation	No	No	Yes (according to building type)	Yes (according to building type)	No
Outside air requirement	No	No	Yes (Not visible, editable, and definable by user except in ABS. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable)	Yes (selectable from the library and user definable)
Default values	N/A	N/A	Yes	Yes	Yes
Recommendation			Yes (according to space type)	Yes (according to activity area type)	Unavailable in input process, available in design guidance advice

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

c. HVAC modeling					
HVAC system	No	No	Yes (Not visible, editable, and definable by user. Not visible to user in GBS result output. Accessible and editable in gbxml and DOE-2 files exported from GBS. Gbxml and DOE-2 files cannot be imported into GBS by user)	Yes (editable and user definable)	No
Default system	No	No	Yes	Yes	No
Recommendation	No	No	Yes (according to building type and floor area)	Yes (according to building type and heating/cooling source)	No
System sizing	No	No	Yes (Not visible in GBS result output)	Yes (Autosize available. Sizing info not visible in eQUEST report output)	No
VI. Result output					
Output export	Yes (text, bitmap output)	Yes	No	No	No
Format of report					
Numeric	Yes	Yes	Yes	Yes	Yes (total net heat flow and breakdown by building element)
Graphic	Yes	Yes	Yes	Yes	Yes (total net heat flow, breakdown of heat gains and losses by building element)
Tabulated data	Yes	Yes	Yes	Yes	Yes
Spreadsheet	No	No	No	No	No
Data visualization	Yes	Yes	No	No	Yes (with animation and sound effect)
Types of report					
Single runs report	Yes	Yes	Yes	Yes	Yes

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

VI. Result output					
Comparative runs report	No	No	No	Yes	No
Content of report					
Parameter					
Temperature profile	Yes	Yes	No	No	No
Heat gain/loss	Yes (fabric, indirect solar, direct solar, ventilation, internal, interzonal gains)	Yes	Not visible in GBS result output. Available in gbxml file exported from GBS	Not visible in eQUEST graphic result output. Available in detailed simulation output file	Yes
Zone load	Yes	Yes	Not visible in GBS result output. Available in gbxml file exported from GBS	Not visible in eQUEST graphic result output. Available in detailed simulation output file	No
Building load	Yes	Yes	Not visible in GBS result output. Available in gbxml file exported from GBS	Not visible in eQUEST graphic result output. Available in detailed simulation output file.	No
Building energy use	No	No	Yes	Yes	No
Breakdown of building energy use	No	No	Yes	Yes	No
Utility bills	Yes (equipment only)	No	Yes	Yes	No
Frequency					
Building lifecycle value	Yes	No	Yes (30 years)	Yes	No
Annual value	Yes	Yes	Yes	Yes	No
Monthly values	Yes	Yes	No	Yes	No
Daily values	Yes	Yes	No	No	Yes
Hourly values	Yes	Yes	No	No	Yes
Summary					
Total	Yes	Yes	Yes	Yes	Yes
Average	No	No	No	Yes	No
Peak	Yes	Yes	Yes	Yes	Yes

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

Building types in GBS	Space types in GBS		
Automotive facility	Active storage	Electrical or mechanical	Other televised playing area sports
Convention center	Active storage hospital or healthcare	Elevator lobbies	arena
Courthouse	Air or train or bus baggage area	Emergency hospital or healthcare	Parking area attendant only parking
Dining bar lounge or leisure	Airport concourse	Equipment room manufacturing facility	garage
Dining cafeteria fast food	Atrium each additional floor	Exam or treatment hospital or healthcare	Parking area pedestrian parking garage
Dining family	Atrium first three floors	Exercise area exercise center	Patient room hospital or healthcare
Dormitory	Audience or seating area penitentiary	Exercise area gymnasium	Personal services sales area retail
Exercise center	Audience or seating area exercise center	Exhibit space convention center	Pharmacy hospital or healthcare
Fire station	Audience or seating area gymnasium	Fellowship hall religious buildings	Physical therapy hospital or healthcare
Gymnasium	Audience or seating area sports arena	Fine material warehouse	Playing area gymnasium
Hospital or healthcare	Audience or seating area convention center	Fine merchandise sales area retail	Police station laboratory police or fire
Hotel	Audience or seating area motion picture theatre	Fire station engine room police or fire station	station
Library	Audience or seating area performing arts theatre	Food preparation	Public and staff lounge hospital or healthcare
Manufacturing	Audience or seating area religious	Garage service or repair automotive facility	
Motel	Audience or seating area police or fire stations	General high bay manufacturing facility	Reading area library
Motion picture theatre	Audience or seating area courthouse	General low bay manufacturing facility	Reception or waiting transportation
Multi family	Audience or seating area auditorium	General exhibition museum	Reception or waiting motel
Museum	Bank customer area	Hospital nursery hospital or healthcare	Reception or waiting hotel
Office	Banking activity area office	Hospital or medical supplies hospital or healthcare	Recovery hospital or healthcare
Parking garage	Barber and beauty parlor		Restoration museum
Penitentiary	Card file and cataloguing library	Hospital or radiology hospital or healthcare	Restrooms

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

Building types in GBS	Space types in GBS		
Performing arts theatre	Classroom or lecture or training penitentiary	Hotel or conference center conference or meeting	Ring sports area sport arena
Police station	Classroom or lecture or training		Sleeping quarters police or fire station
Post office	Confinement cells penitentiary	Inactive storage	Sorting area post office
Religious building	Confinement cells court house	Judges chambers court house	Specialty store sales area retail
Retail	Conference meeting or multipurpose	Laboratory office	Stacks library
School or university	Corridor or transition	Laundry ironing and sorting	Stairs inactive
Sports arena	Corridor or transition manufacturing	Laundry washing hospital or healthcare	Stairway
Town hall	Corridors with patient waiting exam hospital or healthcare	Library audio visual library audio visual	Supermarket sales area retail
Transportation		Living quarters dormitory	Terminal ticket counter transportation
Warehouse	Court sports area sports arena	Living quarters motel	Workshop workshop
Workshop	Courtroom court house	Living quarters hotel	Worship pulpit choir religious
	Department store sales area retail	Lobby	
	Detailed manufacturing facility	Lobby religious buildings	
	Dining area	Lobby motion picture theatre	
	Dining area hotel	Lobby auditorium	
	Dining area family dining	Lobby performing arts theatre	
	Dining area lounge or leisure dining	Lobby post office	
	Dining area motel	Lobby hotel	
	Dining area transportation	Lounge or recreation	
	Dining area penitentiary	Mall concourse sales area retail	
	Dining area civil services	Mass merchandising sales area retail	
	Dormitory bedroom	Medium or bulky material warehouse	
	Dormitory study hall	Merchandising sales area retail	
	Dressing or locker or fitting room gymnasium	Museum and gallery storage	
	Dressing or locker or fitting room court house	Nurse station hospital or healthcare	

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

Building types in GBS	Space types in GBS		
	Dressing or locker or fitting room performing arts	Office enclosed	
	theatre	Office open plan	
	Dressing or locker or fitting room auditorium	Office common activity areas inactive storage	
	Dressing or locker or fitting room exercise center	Operating room hospital or healthcare	

Building Types in eQUEST	Activity Area Types in eQUEST
Community center	Auditorium
Conference/convention center	Auto repair workshop
Health/fitness center	Bank/financial institution
Heath, hospital (inpatient)	Bar, cocktail lounge
Health, long-term care (nursing home)	Barber and beauty shop
Health, medical clinic/prof. building (outpatient)	Casino/gaming
Lodging, motel	Classroom/lecture
Lodging, high-rise hotel	Courtroom
Multifamily, low-rise (exterior entries)	Comm/ind work (general, high bay)
Multifamily, mid-rise (interior entries)	Comm/ind work (general, low bay)
Multifamily, high-rise (interior entries)	Comm/ind work (precision)
Museum	Conference room
Office bldg, high-rise	Convention and meeting center
Office bldg, mid-rise	Copy room (photocopying equipment)
Office bldg, two story	Corridor
Office bldg, bank/financial	Dining area
Religious worship	Dry cleaning (coin operated)
Restaurant, full service (full menu)	Dry cleaning (full service commercial)
Restaurant, quick service (fast food)	Exercising centers and gymnasium
Restaurant, bar/lounge	Exhibit display area/museum
Retail, department store	Hotel/motel guest room (incl. toilets)
Retail, large single story	Kitchen and food preparation
Retail, stand-alone structure	Laboratory, medical
Retail, single storefront	Laundry
Retail, strip mall	Library (reading areas)
Retail, service station	Library (stacks)
Retail, service station/convenience store	Lobby (hotel)
Retail, warehouse sales	Lobby (main entry and assembly)

Sustainability Performance Simulation Tools for Building Design. Table 3 (Continued)

Building Types in eQUEST	Activity Area Types in eQUEST
School, preschool/daycare	Lobby (office reception/waiting)
School, k-6 elementary	Locker and dressing room
School, middle school	Mall, arcade and atrium
School, college/university	Mechanical/electrical room
Storage, conditioned high bay	Medical and clinical care
Storage, unconditioned high bay	Office (general)
Storage, conditioned low bay	Office (executive/private)
Storage, unconditioned low bay	Office (open plan)
Theater/performing arts	Police station and fire station
Unknown, custom or mixed use	Religious worship
	Residential (high-rise)
	Residential (multifamily dwelling unit)
	Residential (single family)
	Restrooms
	Retail sales and wholesale showroom
	Smoking lounge
	Storage (conditioned)
	Storage (unconditioned)
	Theater (motion picture)
	Theater (performance)
	Vocational areas
	Unknown

[a]Definition of *Built-in Library* as a selection of specific cases with complete and realistic description of relevant input parameter

Conclusions and Recommendations

Research by Lam et al. [41] has demonstrated the web-based service approach to energy modeling tool design has distinct advantages of being platform independent, allowing distributed collaborations, ease of maintenance and updates, better resource support and availability, and arguably lower costs. The development of GBS as a web-based service has shown the same benefits.

The user interface should be designed such that it is familiar, cognitive, and complements the concepts and processes of architectural design and energy modeling. With respect to operation within the Windows environment, Ecotect has been exemplary in providing a well-designed user interface that is easy to use.

Technical help, guidance, and documentation are important to the usability of software. Ecotect has comprehensive help files, tutorials, and the user forum was very useful. TAS and GBS have taken a new approach to providing guidance by providing videos. Only eQUEST provides detailed technical documentation, which is considered to be important given the nature of energy modeling, but may not be a dominant issue during the early design phase.

Geometric acquisition for energy modeling has traditionally been a tedious and error-prone process.

Sustainability Performance Simulation Tools for Building Design. Table 4 Definition of items in the evaluation matrix

Item	Description
1. SYSTEM	
Operating platform	
Windows	Tool operates within Windows environment without additional software or emulators
Mac OS	Tool operates within Macintosh environment without additional software or emulators
Unit system	Measurement units used by the tool
Energy design guidance	Assistance in conducting energy simulations, such as guidance on simulation workflow and appropriate modeling methods
Built-in library	
Weather data	Availability of selection of specific cases with complete and realistic description of relevant input parameter
Material	
Construction	
Schedule	
Internal heat gain	
Infiltration	
HVAC system type	
HVAC equipment	
Simulation application	
Stand-alone	Simulation conducted on local workstation
Web-powered	Simulation conducted on off-site server via network
Program stability	The ability of the tool to continue operations and maintain correctness under an amplitude of input changes
Weather file	Method used to select climatic data
Types of weather files	Format of climatic data used
History Tracking	
Undo/redo	The tool keeps track of states allowing the feature of redo and undo
Error logging	The tool maintains an error log upon failures
II. Extension	
Interoperability	
IFC compliance	The tool allows import/export of data in IFC format without additional software
File exchange with other energy simulation tools	The tool allows import/export of complete energy model data with other simulation tools without additional software or intervention
File exchange with CAD tools	The tool allows import/export of complete geometric data with CAD systems without additional software or intervention
Drawing data input	
Import as underlay	The tool allows import of 2D drawings from CAD systems to facilitate geometric modeling

Sustainability Performance Simulation Tools for Building Design. Table 4 (Continued)

Item	Description
Building element import	The tool allows import of 3D elements from CAD systems to facilitate geometric modeling
III. Functionality	
Technical approach	Simulation engine used by the tool
Types of energy calculation	
Building load calculation	Calculation of building heating, cooling, and electricity load
Building energy simulation	Calculation of energy consumption by the various equipments in the mechanical system, in order to meet the building heating, cooling, and electricity load
Parametric operation	
Single run/single input and output	Tool allows simulation of a model and presents the results
Batch Processing	Tool allows queuing of multiple models for simulation
Code compliance	Tool includes features to consider if the results of the energy models comply with regulations
Cost estimation	Tool includes features to estimate the costs related to the building that is being modeled
IV. User	
Documentation	
Tutorial/manuals/wizard	Types of documentation available to assist in learning how to use the tool and understanding the workflow
Engineering documentation	Technical documentation explaining the computational processes, methods, and assumptions used by the tool
Help function	Integrated help feature by button, keystroke, or menu to assist in using the tool interface and explaining the workflow
User support	Types of resources available to users in learning the tool
File save interval	Restrictions on when the user can invoke the save command
Navigation between windows	Restrictions on the user to toggle between different windows: Flexible – Tool allows user to toggle between windows in no particular sequence, Random – Tool allows user to toggle between any two windows
Clarity of menu and tool bars	The organization and naming of the menu and tool bars are with clarity
Model view	Allows user to view the energy model geometrically
Model display	Shading methods available when viewing the energy model
Expertise required	General expertise required of user to use the tool effectively
V. Modeling	
Zone management	Method used to manage the thermal zones in the energy model
a. Project information	
Building type definition	Tool allows user specification of building type to check, modify, or recommend various parameter settings
Space type definition	Tool allows user specification of space type to check, modify, or recommend various parameter settings

Sustainability Performance Simulation Tools for Building Design. Table 4 (Continued)

Item	Description
b. Building modeling	
Geometry	
Space composition	
Buildup by spaces	Tool allows geometric model to be constructed additively
Subdivision of floor plate	Tool allows modeled elements to be subdivided
Direct drawing input	
Primitive shapes	Tool allows modeling by selecting basic forms Boolean operations
Extrusion based on closed curve	Tool allows modeling by drawing profiles and extruding
Surfaces	Tool allows modeling by constructing surfaces
Building element definition	Tool allows specification and modification of individual elements as various building element types
Different heights within floor	Tool allows different spaces on the same level of the model to have different floor to ceiling heights
Sloped roof	Tool allows the modeling of sloped roofs
Sloped floor	Tool allows the modeling of sloped floors
Building orientation	Tool allows the north direction to be modified via a single orientation parameter
Accessible coordinate data	Tool shows the dimensions of each element and allows them to be changed by direct numerical input
Snap function	Tool provides modeling snap-to-point features
Modification	Tool allows modeled elements to be transformed geometrically
Geometry checking	Tool provides features to check that the geometric model has been constructed properly
Building construction	
Material	Notes on how the tool allows the user to define materials
Layer	Notes on how the tool allows the user to define layers
Construction	Notes on how the tool allows the user to define constructions
Shades	Notes on how the tool allows the user to model sun shading devices
Default values	Tool specifies some realistic default construction properties for building elements based on some project information such as type of building or space being modeled
Recommendations	Tool makes recommendations for construction types and material values based on some project information such as type of building or space being modeled
Internal loads	
Occupant	
Load	
Density	Tool allows variation of occupancy density across different spaces
Total Number of occupants	Tool allows specification and modification of number of occupants
Schedule	Tool allows specification of a schedule for occupancy

Sustainability Performance Simulation Tools for Building Design. Table 4 (Continued)

Item	Description
Lighting	
Load	
Density	Tool allows variation of lighting loads across different spaces
Individual appliance	Tool allows specification of individual light appliances within each space
Schedule	Tool allows specification of a schedule for lighting loads
Equipment	
Load	
Density	Tool allows variation of equipment loads across different spaces
Individual appliance	Tool allows specification of individual electrical appliances within each space
Schedule	Tool allows specification of a schedule for electrical loads
Default values	Tool specifies some realistic default internal loads conditions based on the type of building or space being modeled
Recommendations	Tool makes recommendations for internal load conditions based on some project information such as type of building or space being modeled
Infiltration	
Rate	Tool allows specification of infiltration rates
Schedule	Tool allows specification of a schedule for infiltration
Default values	Tool specifies some realistic default infiltration conditions based on the type of building or space being modeled
Recommendations	Tool makes recommendations for infiltration conditions based on some project information such as type of building or space being modeled
Utility	
Rate	Tool allows specification of utility rates
Schedule	Tool allows specification of a schedule utility rates
Default values	Tool specifies some realistic default utility rates based on some project information such as type of building being modeled or location of building
Recommendations	Tool makes recommendations for infiltration conditions based on some project information such as type of building being modeled or location of building
c. HVAC modeling	
Thermostat set point	Tool allows specification of heating and cooling set points for each zone in the HVAC system
HVAC zoning	Tool allows specification of HVAC zones from the spaces defined by the geometric building model
Relationship between HVAC zone and building space	Relationship between HVAC zones and spaces defined by the geometric building model
Zone Grouping	Tool allows several zones to be grouped in a hierarchical manner
HVAC schedule	Tool allows specification of a schedule for HVAC operations
Default values	Tool specifies some realistic default HVAC schedules based on some project information such as type of building or space being modeled

Sustainability Performance Simulation Tools for Building Design. Table 4 (Continued)

Item	Description
Recommendations	Tool makes recommendations for HVAC scheduling based on some project information such as type of building or space being modeled
Outside air requirement	Tool allows specification of outside air requirements as part of HVAC system
Default values	Tool specifies some realistic default outside air requirements based on some project information such as type of building or occupancy being modeled
Recommendations	Tool makes recommendations for outside air requirements based on some project information such as type of building or occupancy being modeled
HVAC system	Tool allows specification of the type of HVAC system
Default system	Tool specifies some realistic default HVAC system based on some project information such as type of building being modeled
Recommendations	Tool makes recommendations for HVAC system based on some project information such as type of building being modeled
System sizing	Tool includes feature to size the HVAC system accordingly
VI. Result output	
Output export	Tool allows simulation results to be exported for processing in other spreadsheet or analysis applications
Format of Report	
Numeric	Tool produces numerical reports of simulation results
Graphic	Tool produces graphical reports of simulation results
Tabulated data	Tool produces tabular reports of simulation results
Spreadsheet	Tool produces spreadsheets from simulation results
Data visualization	Tool includes some features of presenting the data in visuals that assist in understanding the thermal performance predicted by simulation
Types of report	
Single runs report	Tool produces reports for a single simulation
Comparative runs report	Tool presents results from multiple simulations on a single report for comparison
Content of report	
Parameter	
Temperature profile	Report on outdoor mean air temperature and mean space temperature for all spaces
Heat gain/loss	Report on heat gain/loss for all spaces
Zone load	Report on all zone loads
Building load	Report on building load
Building energy use	Report on active building energy use
Breakdown of building energy use	Report on active building energy use breakdown
Utility bills	Report on building utility bills
Frequency	
Building lifecycle value	Reports presented over lifecycle of building with appropriate time values

Sustainability Performance Simulation Tools for Building Design. Table 4 (Continued)

Item	Description
Annual value	Reports presented as cumulative annual values
Monthly values	Reports presented as 12 monthly values
Daily values	Reports presented as 365 daily values
Hourly values	Reports presented as 8,760 hourly values
Summary	
Total	Reports include a total value
Average	Reports include an averaged values
Peak	Reports indicate maximum and minimum value occurrences

The advances of Ecotect in allowing 3D CAD model import and fully automatic geometric acquisition from imported CAD files by GBS is heartening.

Different technical approaches have different semantic and spatial limitations. It is important that the user receives timely and detailed feedback on the correctness of the geometry that he/she has defined. This should be the case even if the geometry acquisition is totally automated.

In general, extensive library support and appropriate recommendations for constructions and materials are important for the designers, especially in the early design phase. Comprehensive weather data should also be made available.

The postprocessing functionalities in the selected tools are limited to conventional numerical and graphical reports of values such as loads and temperatures. It would be desirable to develop visualizations that would better facilitate a qualitative understanding of the design performance to the user and provide appropriate guidance in the context of early design decision making.

With respect to the early design phase as an adaptive-iterative process, energy modeling tools should ideally be able to support parametric studies. This is generally lacking in contemporary energy modeling tools.

The information content provided by the various tools varies tremendously. There is a need to clarify the information needs of the early design phase and to match the provisions accordingly.

For a tool to be beneficial and remain relevant throughout the building delivery process, it would be advantageous if it is developed based on comprehensive and fundamental principles in modeling the building-environment interactions. The tendency to adopt abstraction and rule-of-thumb approaches in an attempt to meet the time and resource constraints encountered in early design should be avoided. By offering different sets of user interfaces that automate and reveal parameters on different levels of granularity, it is possible for a tool to support various design phases effectively.

Integrated Building Design and Operation Process Modeling

Notwithstanding the advancement in modeling tool developments, it can be argued that any model that is created during the design phase will never be able to truly and accurately represent the as-built and operational realities of a building. There are simply too many variables involved in the building delivery process and the building operation phase that are difficult to assure that the specified properties are achieved and assumed occupational schedules are indeed maintained. However, if the model is created with high fidelity and solidly based on first-principle physical constructs, it can in fact be continuously used in the operational phase of the building as part of the integrated building management and control system. The assumed values of parameters used in the original design for predicting the building performance can now be replaced by real operational data acquired through an environmental sensor network (both indoor and outdoor) and from the building management system. The model can thus be empirically recalibrated[5] and then used to conduct advanced predictive control of building operations.

Role of Building Control in Energy Consumption Reduction

Buildings are responsible for at least 40% of energy use in many countries, mostly derived from fossil fuels. Worldwide building energy consumption is expected to grow 45% over the next 20 years [42]. In the United States, commercial buildings consume almost 17% of national energy use. Seventy-six percent of the services used by buildings (e.g., heating, cooling, lighting, etc.) are powered by electricity, and these account for 35% of the total electricity consumed nationally [43]. Heating, ventilation, and air-conditioning (HVAC) systems in commercial buildings account for nearly 37% of the total building energy.

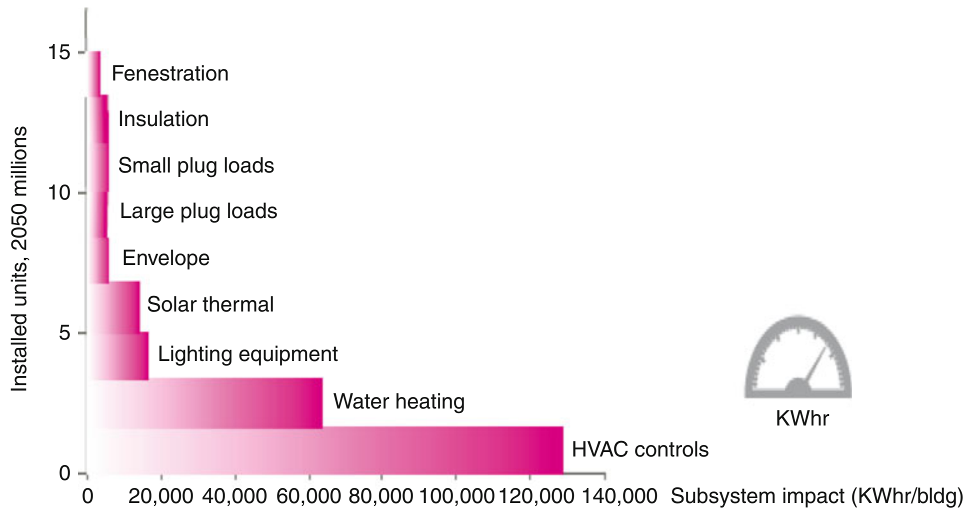
According to the market surveys conducted by Brambley et al. [44], building controls can potentially reduce energy consumption significantly in commercial buildings. Table 5 demonstrates how a traditional Energy Management and Control System (EMCS) can save between 5% and 15% of a building's energy with an 8–10-year return on investment for the system, while occupancy sensors for lighting control can save 20–28% energy with 1–5 years payback on the initial investment. In addition, one of the objectives of control system is to improve the indoor environmental performance (e.g., thermal, lighting, and air quality). Figure 10 further illustrates that HVAC controls have potentially the biggest impact on the building energy consumption, yet there are relatively few installations in multifamily residential developments [45]. Furthermore, the Building Investment Decision Support Tool developed by the Center for Building Performance and Diagnostics at Carnegie Mellon University has identified 20 studies that link improved temperature control to productivity gains, with an average 5.5% productivity increase within a range of between 1.2% and 24% [46].

Typical control functions in buildings can be divided into two categories: local control and

Sustainability Performance Simulation Tools for Building Design. Table 5 Summary of energy-saving potentials for different control approaches (Brambley et al. [44])

Control technology	Technical market size (billions ft^2)	Relevant primary energy (quads)	Energy savings (%)	Technical energy savings potential (quads)	Simple payback period (years)	Remaining market penetration	Market-achievable energy savings (quads)
Energy management and control system (EMCS)	33	6.2	5–15%	0.3–0.9	8–10	5–10%	0.02–0.09
Commissioning	55	9.8[a]	5–15%	0.5–1.5	2–10	3–30%	0.015–0.5
Automatic fault detection and diagnostics (AFDD)/ Continuous commissioning	55	9.8[a]	5–15%	0.5–1.5	1–3	15–55%/ 6–24%	0.07–0.8/ 0.03–0.35
Occupancy sensors for lighting control	50	3.5	20–28%	0.7–1.0	1–5	0–45%	0–0.45
Photosensor-based lighting control	55	3.9	20–60%	0.8–2.3	1–7	8–55%	0.08–1.3
Demand controlled ventilation (DCV)	55	5.4	10–15%	0.5–0.8	2–3	15–30%	0.08–0.25

[a]This figure includes 0.5 quads for supermarket refrigeration systems and walk-in refrigeration



Sustainability Performance Simulation Tools for Building Design. Figure 10
Energy-saving potentials for HVAC control (cp. World Business Council for sustainable development [45])

supervisory control. Local control provides basic control and automation functions, such as ON/OFF control and proportional-integral-derivative (PID) control that allow building services to operate properly. Many studies show that local controls can provide thermal comfort and satisfy goals for indoor air quality (Moore and Fisher [47]; Nassif et al. [48]; Zhang and Hanby [49]). Supervisory control functions are higher level controls that include local control functions while considering whole system characteristics (both active HVAC and passive systems), interaction, and energy optimization for total building energy saving. Supervisory control functions are developed using the physical model–based method, hybrid method, performance mapping method, and data learning approach [50]. In the last decade, research has increasingly focused on supervisory control to expand the opportunities for greater energy savings.

Modeling Building Control Design and Operation

Building control design and operation need consistent and reliable static and dynamic information from various resources to feed into the set of fundamental governing thermal dynamic equations. Table 6 summarizes the informational requirements for the design and operation of a model-based building control system.

Model-based predicted control can help optimize energy use while maintaining the appropriate indoor set-point temperature when the spaces are occupied. However, several barriers in many of the current approaches of building control design and operation impede the full achievement of this goal. For instance, (a) dynamic data are not readily available such as real-time site weather (e.g., temperature, wind speed, and solar radiation) and occupancy status (number as well as duration in the space); (b) a comprehensive whole building energy model is not fully integrated into advanced controls for accuracy and robustness; (c) real-time implementation cases of such control on indoor thermal environment are rare.

Dong [51] recently published his PhD dissertation to address some of these limitations in implementing integrated building control. A comprehensive literature review was conducted on the topics of (1) model-based supervisory control and optimization techniques for building HVAC systems and (2) occupancy detection and behavior prediction in buildings.

Model-Based Supervisory Control and Optimization Techniques A summary of main optimization techniques used in building HVAC supervisory controls is given in Table 7.

Sustainability Performance Simulation Tools for Building Design. Table 6 Information requirements for the design and operation of a model-based building control system

Information type	Information elements	
Input parameters during control design stage		
Geometry information	Static information	Wall, doors, and windows surface areas
		Number of thermal zones and volumes
		External surface orientation, tilt and azimuth
Construction information	Static information	External/internal wall, window, and door construction type
		Material properties: thickness, thermal conductivity, specific heat, solar transmission, etc.
Internal zone information	Dynamic information	Internal gains: occupancy number and schedule, equipment, and use schedule
		Indoor temperature set-point, air flow rate, etc.
System information	Static information	HVAC system type (chiller, heat pump, fan coil, etc.) and their physical parameters
		Duct or pipe physical parameters such as length
	Dynamic information	Designed operation information
Weather information	Dynamic information	Outdoor temperature, solar radiation, wind velocity, etc.
Data resources during operation		
Static information	CAD MEP drawings, construction, and material specification	
	Predefined schedules for HVAC systems, occupancy, lighting, etc.	
Dynamic information	Real-time HVAC system performance from sensors in systems such as supply air temperature, supply air flow rate, return air temperature, relative humidity	
	Real-time indoor environmental measures from sensors such as temperature, RH, CO_2, air flow, etc. and dynamic occupancy information from sensors	
	Dynamic usage of internal equipment from power metering	
	Historical/simulated weather information, on-site weather measurements	

Occupancy Detection and Behavior Prediction Occupant presence and behavior in buildings has been shown to have large impacts on space heating, cooling and ventilation demand, energy consumption of lighting and space appliances, and building controls [66]. Several stochastic models have been developed to model occupant presence and interactions with space appliances and equipment. Fritsch et al. [67] proposed a model based on Markov chains to model the random opening of windows by occupants. Degelman [68] developed a Monte Carlo modeling approach for space occupancy predictions based on survey statistics. Reinhart [69] determined occupant presence for lighting simulation by using a simplified stochastic model of arrival and departure. Wang et al. [70] applied Poisson distributions to generate daily occupancy profiles in a single-occupied office. Bourgeois et al. [71] integrated an occupancy model based on Reinhart's algorithm into ESP-r to investigate lighting application. Most of these occupancy presence models were either tested on a single-person office or presented as a specific application such as lighting control. More

Sustainability Performance Simulation Tools for Building Design. Table 7 Summary of main optimization techniques used in building HVAC supervisory controls

	Techniques	Research studies	Strength	Weakness
Nonlinear local techniques	Direct search	Zaheer-uddin and Zheng [52]; Xu and Haves [53]	Simple and easy to be understood and implemented. No derivatives are required	Often fails to obtain an optimal solution and less computationally efficient
	Sequential quadratic programming	House and Smith [54]; Kota et al. [55]; Sun and Reddy [56]	Handles a large number of inequality	Has to start from initial guess values and the speed is affected by its initial values
			Constraints efficiently	
	Lagrange method	Chang [57]; Sane and Guay [58]	Easy to be implemented since Lagrange formula does not depend on the order in which the nodes are arranged	The convergence is not always guaranteed
Nonlinear global techniques	Simulated annealing	Flake [59]; Chang et al. [60]	Relatively easy to be implemented	High computational costs and memory demands
	Evolutionary algorithms and genetic algorithm	Henze et al. [61]; Wang and Jin [62]; Xing [63]; Kummert [64]; Zhang and Hanby [49]; Coffey [65]	With high generalities and flexibilities, and they are also robust in finding the global minimum	Extensive computational costs and memory demands due to a high number of fitness evaluations

recently, Page et al. [72] targeted individual occupancy behaviors by developing a generalized stochastic model for the simulation of occupant presence with derived probability distributions based on Markov chains. However, such a stochastic model was based on the assumption that occupants will interact with different appliances in the space, and the validation was conducted in single-person-occupied offices. Other current approaches to occupancy detection take place mostly in commercial buildings through the use of passive infrared (PIR) motion detectors. Motion detectors have inherent limitations when occupants remain relatively still. Moreover, motion detectors alone only provide information regarding the presence or absence of people in a space rather than the number of occupants, information which is highly useful for building control tasks such as demand controlled ventilation [73].

Video cameras have also been used to detect human movements in buildings. Trivedi et al. [74] conducted rigorous experimental investigations on the processing and control modules for the active camera networks and the microphone array which are embedded in an intelligent room. The integrated system has the functionality of human tracking, active camera control, face recognition, and speaker recognition. Lymberopoulos et al. [75] developed a system called BehaviorScope for interpreting human activity patterns using a camera network and its application to elder monitoring in assisted living. Notwithstanding the tremendous value of this technique, video capture raises privacy concerns and requires large amounts of data storage.

Other work has focused on the use of carbon dioxide (CO_2) sensors in conjunction with building models for estimating the number of people generating the measured CO_2 level [76, 77]. Recent research on so-called smart environments involves the use of a diverse set of sensors to monitor and infer human activity in a building. Examples include the MIT Intelligent Room [78], the University of Colorado Boulder Neural Network Adaptive Home [79], Georgia Tech Aware Home [80] and the University of Texas at Arlington MavHome [81, 82]. Most of these efforts focus on behavioral modeling or mobility tracking and do not exploit additional sensing capability for the detection of occupancy numbers. In addition to these test beds, Duong et al. [83] used Hidden Semi-Markov models for modeling and detecting activities of daily living such as cooking and eating, and Youngblood and Cook [82] introduced a new method of automatically constructing Hierarchical Hidden Markov models using the output of a sequential data mining algorithm to control a smart environment. Other research endeavors investigate HVAC preconditioning and device automation via mined location and device interaction patterns and the energy-saving potential is estimated through a relatively simple consumption model [84].

A Demonstrative Case Study: The CMU Solar Decathlon House 2005

Based on the above literature review and identification of the apparent "gaps" in the current techniques (see Table 8), Dong [51] introduces and illustrates a novel methodology for integrated building heating, cooling, and ventilation control with the objective to reduce energy consumption and maintain indoor temperature set-point, based on the prediction of occupant behavior patterns and weather conditions. Several advanced machine learning methods such as Adaptive Gaussian Process, Hidden Markov Model, Episode Discovery, and Semi-Markov Model were modified and implemented. A nonlinear model predictive control (NMPC) was designed and implemented in real time based on dynamic programming. The experiment test bed was set up in the Solar Decathlon House (2005) (Fig. 11), with over 100 sensor points measuring indoor environmental parameters such as temperature, relative humidity, CO_2, lighting, motion and acoustics, and the power consumption for electrical plugs, HVAC, and lighting. The outdoor environmental parameters such as temperature, relative humidity, CO_2, global horizontal solar radiation, and wind speed are obtained from an on-site weather station. The designed controller was implemented through LabView.

A first-principle physically based detailed and integrated model of the test bed was constructed which comprises the constituent models of the building geometry, construction materials and thermal zoning (Fig. 12), the energy supply and demand (HVAC) systems (Fig. 13), as well as the optimal building control schema (Fig. 14).

Sustainability Performance Simulation Tools for Building Design. Table 8 Comparisons of integrated HVAC control approaches

Author	Input information for control modeling		Actual implementation		
	Local weather forecasting	Dynamic occupancy patterns	Real time	Fully model-based	High computational speed
Wang and Jin [62]			√		√
Henze et al. [61, 85, 86]			√		
Xu and Haves[53]				√	√
Xing [63]				√	
Sun and Reddy [56]			√		
Kummert and Andre [64]			√	√	
Zhang and Hanby [49]					
Sane and Guay [58]			√		√
Coffey [65]			√	√	
Dong [51]	√	√	√	√	√

Sustainability Performance Simulation Tools for Building Design. Figure 11
The Carnegie Mellon University Solar Decathlon House 2005

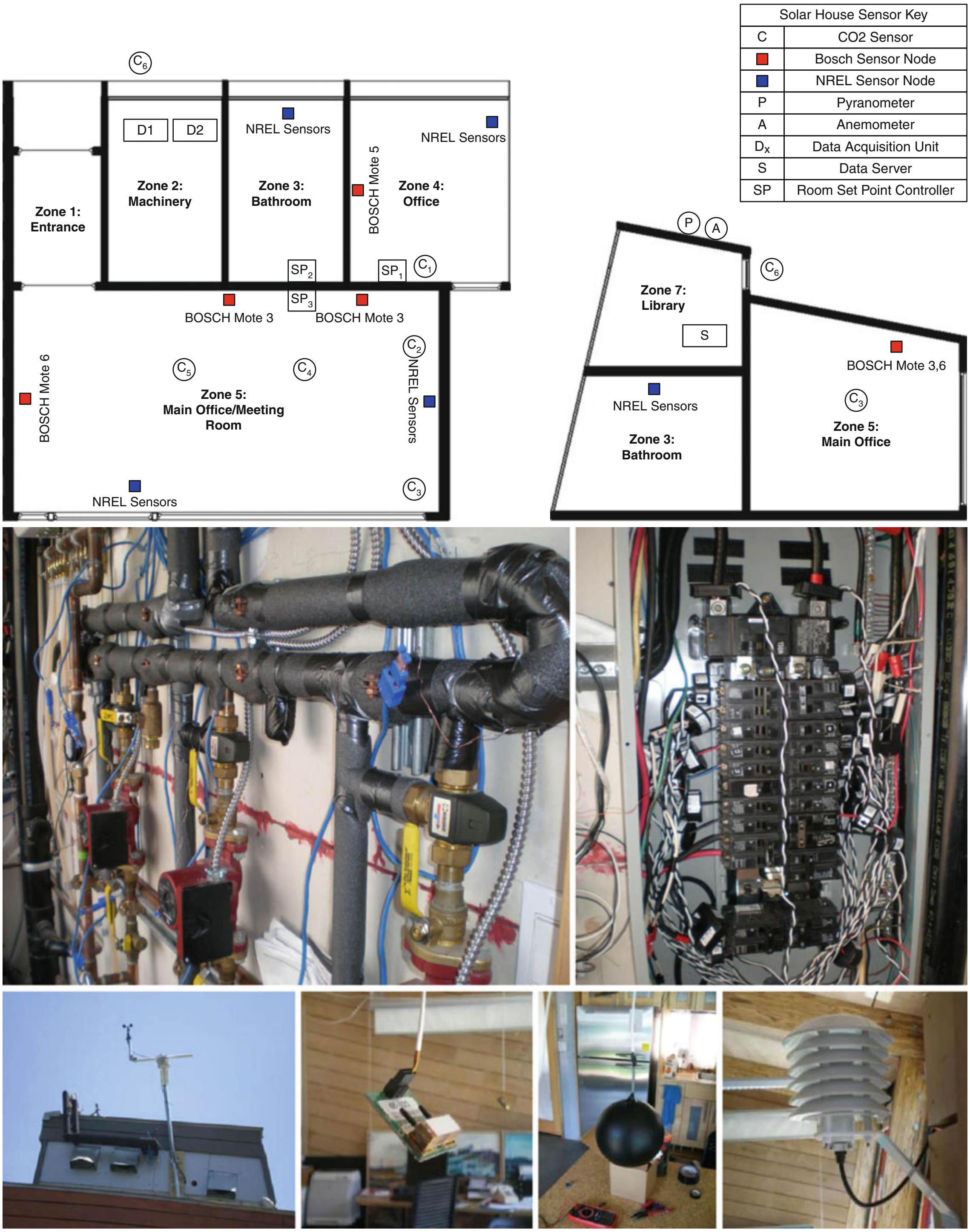
The models were validated through empirical experiments, and studies were conducted for two continuous months in the heating season and for a week in cooling season. Some selected results are presented below.

Figure 15 shows the measured results of energy consumption profile of the NMPC model, which integrates the weather forecasting and occupant behavior pattern prediction. Due to the thermal mass effect of the concrete floor slab, there is no need for additional heating during the daytime on most days during the experimental period, while maintaining the temperature within the set-point bands (see Fig. 16).

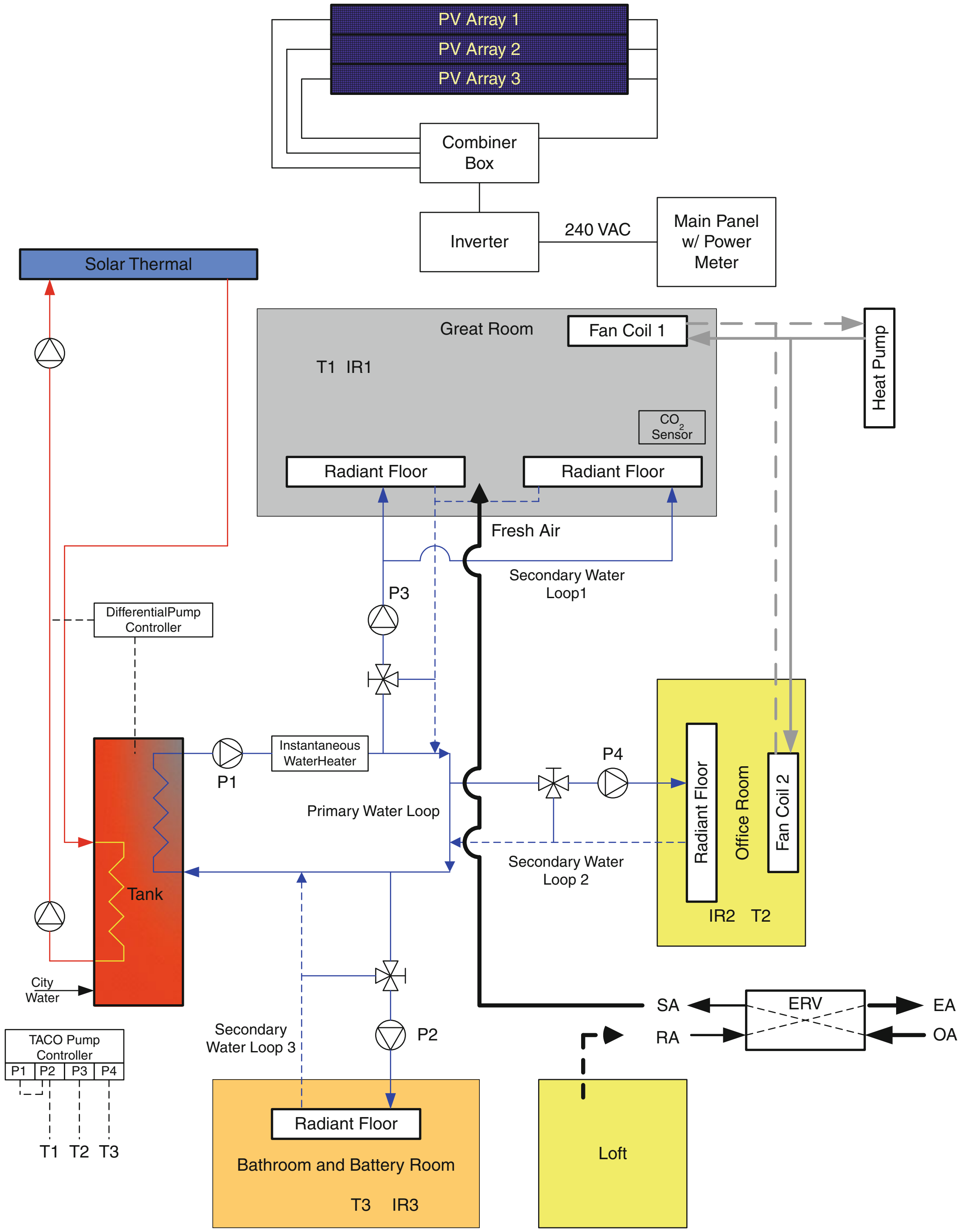
It also shows the comparison of the energy profile between the NMPC model and a "conventional" scheduled set-point model. The scheduled temperature set-point normally has a night setback, which is 17°C in this study. The heating system remains off until the indoor temperature drops below the setback temperature. Hence, the heating system often starts after midnight and at its full capacity in order to reach the desired set-point in the morning. In addition, the actual occupancy period often does not quite match with the scheduled daily temperature set-point period. These conditions result in more energy consumption for scheduled temperature set-points control compared with the proposed integrated control. The energy saving from the integrated control is illustrated in dashed boxes. The integrated control can save 30.1% of energy compared with the scheduled control. Furthermore, the temperature set-point was not met only for 2 h for the integrated control while it was 8 h for the schedule temperature set-point control (see Table 9). This is because during some cold nights when the indoor air temperature is around the night setback (17°C), the daily set-point in the morning cannot be met. Instead, the integrated controls keep the indoor air temperature warm enough at night to meet the set-point in the morning.

Figure 17 compares the energy consumption between NMPC and scheduled set-points during a week in the cooling season. The energy saving mainly comes from the dynamic occupancy scheduling, while the scheduled control set-point method tries to maintain the set-point regardless of whether there is any occupant in the space.

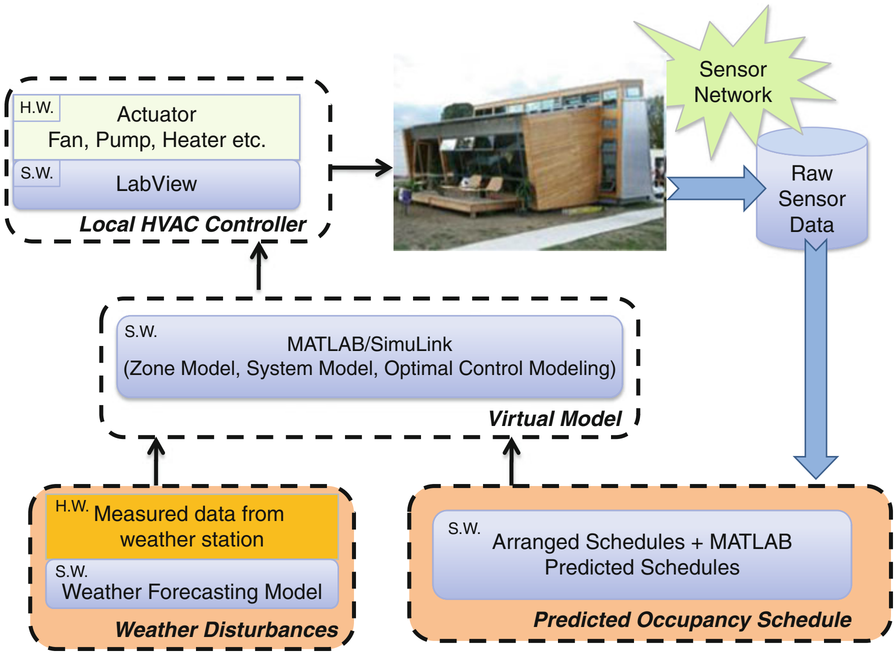
Figure 18 provides a more detailed look at the daily behavior and performance of the system on July 1, 2010. The scheduled set-point maintains the indoor temperature at the set-point, 25°C. The NMPC dynamically controls the temperature based on the actual occupancy level. In addition, the scheduled set-point



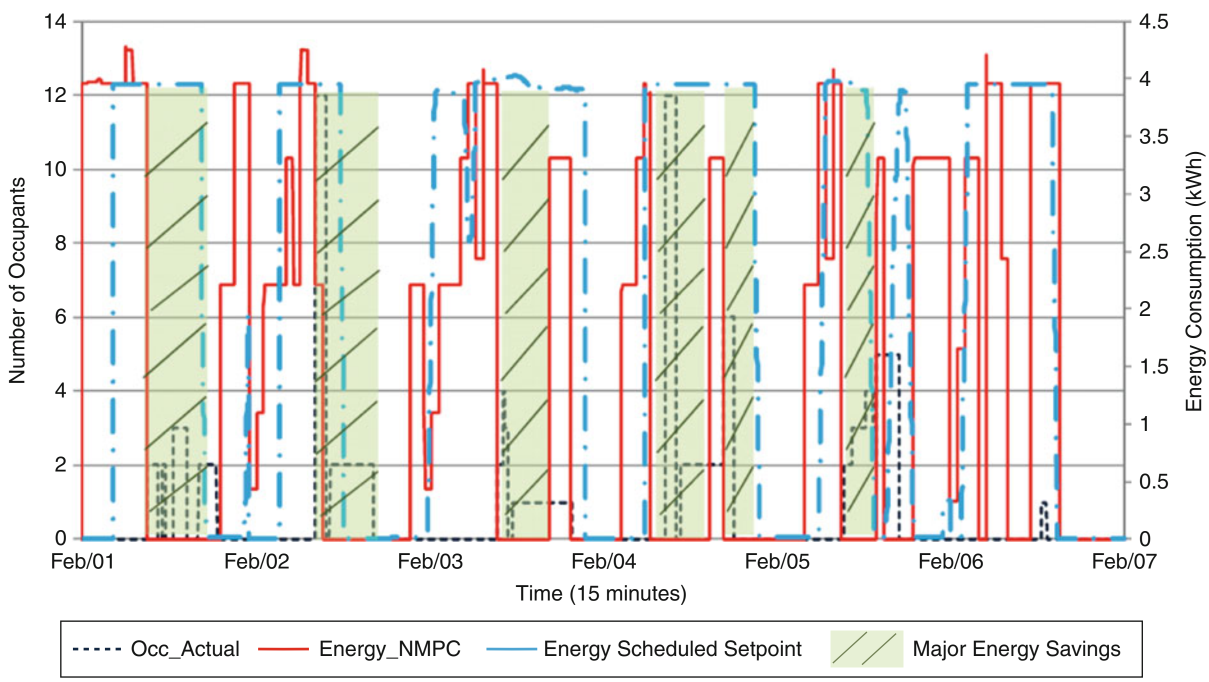
Sustainability Performance Simulation Tools for Building Design. Figure 12
Building geometry, thermal zoning, and sensor system layout



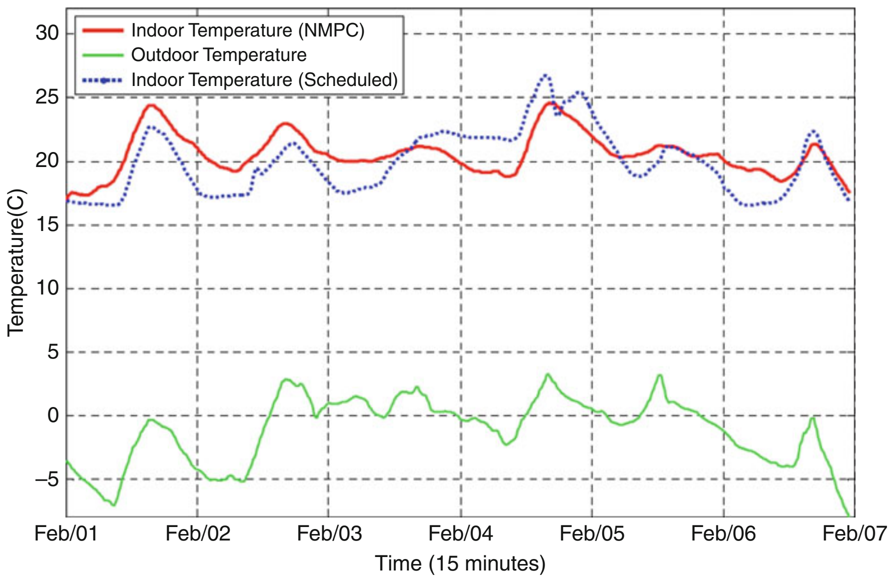
Sustainability Performance Simulation Tools for Building Design. Figure 13
Overview of the energy supply and demand systems



Sustainability Performance Simulation Tools for Building Design. Figure 14
Overview of integrated control (NMPC) implementation schema



Sustainability Performance Simulation Tools for Building Design. Figure 15
Comparison of energy profiles between NMPC and scheduled temperature set-points for the heating season in February 2010



Sustainability Performance Simulation Tools for Building Design. Figure 16
Indoor and outdoor temperature profile from February 1 to February 7, 2010

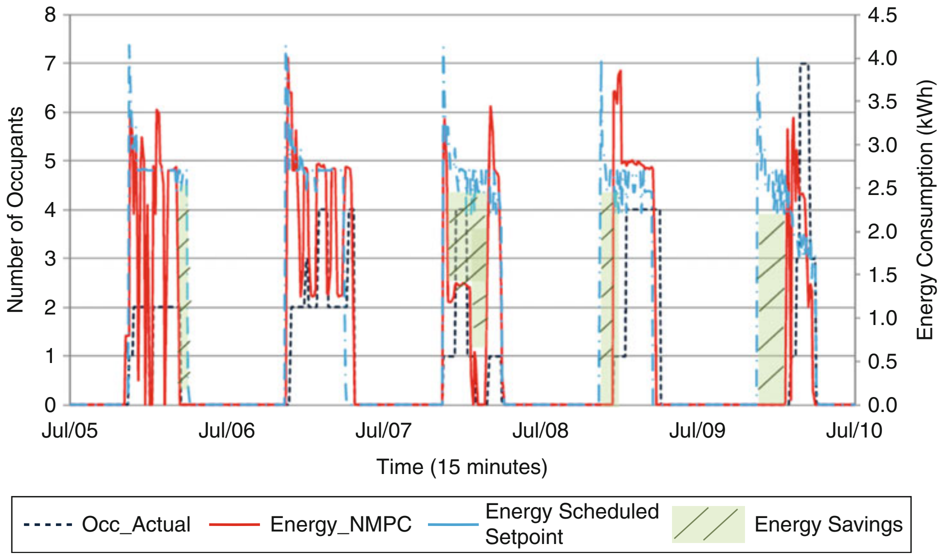
Sustainability Performance Simulation Tools for Building Design. Table 9 Comparison of heating energy consumption and number of hours when temperature set-points are not met

Energy consumption (kWh)		Energy saving (%)
Scheduled temperature set-points	343	30.1
NMPC optimization	240	
Temperature set-point not met while occupied (h)		*Better set-point met time (%)*
Scheduled temperature set-points	8	75
NMPC optimization	2	

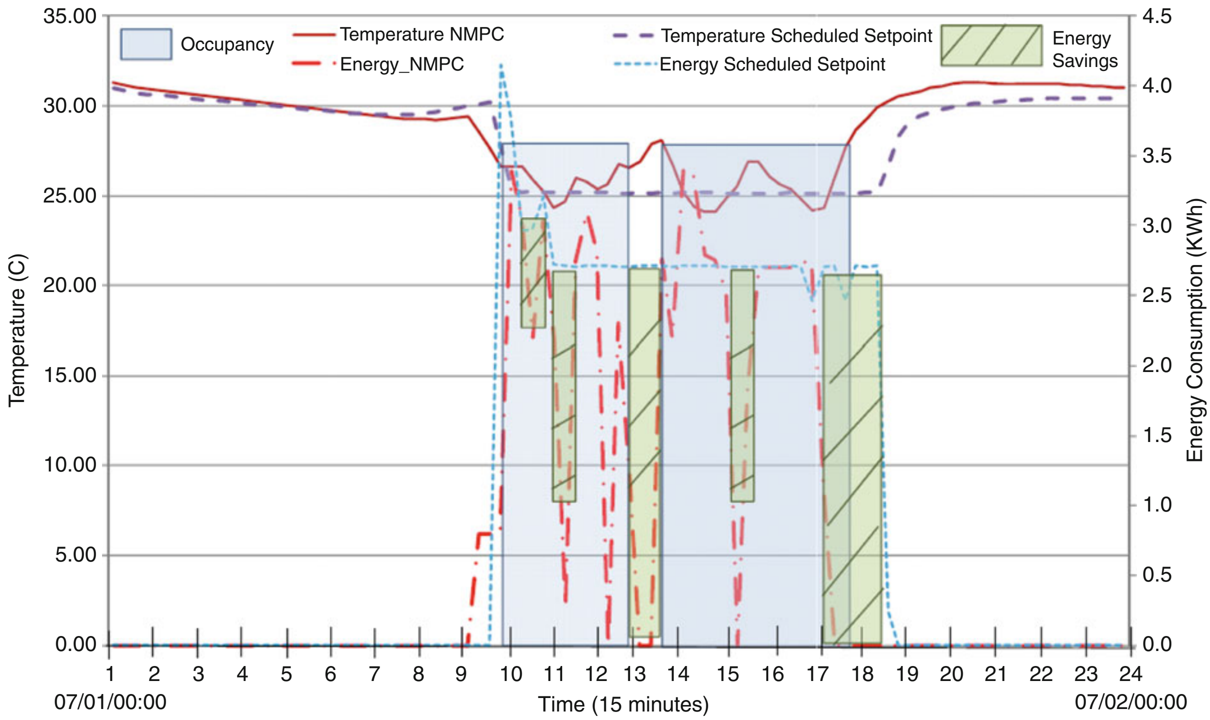
assumes the occupants vacated the premise at 7:00 p.m., while in reality it happened at 5:30 p.m. The NMPC cools down the space in two time steps (30 min) before the occupants arrive, and allows the room temperature to float during lunchtime.

Table 10 compares the simulated energy consumption of schedule set-points and measured NMPC optimization. The total cooling energy saving for the week is 17.8%. Although the dynamic occupancy schedule varies with cooling set-points in the space, the temperature of the space changes quickly so that the energy saving is only realized over a short duration of about an hour (four 15-min time steps).

To investigate further energy saving possibilities, a model with better building envelop performance is conducted. The air infiltration rate for the meeting room in the test bed is found to be 0.6 air change per hour (ACH). However, a good benchmark of a tight envelop should be 0.3 ACH. With this improved value, there is a further increase in energy saving and the number of hours whereby the set-point temperature is not met is also reduced. While the pre-cooling time becomes slighting longer with 3–4 time step ahead of occupant's morning arrival instead of 1 time step, the cooling system shuts down several time steps earlier before the occupants leave the room.



Sustainability Performance Simulation Tools for Building Design. Figure 17
Comparison of energy profiles between NMPC and scheduled temperature set-points for the cooling season in July 2010



Sustainability Performance Simulation Tools for Building Design. Figure 18
Comparison of energy profiles between NMPC and scheduled temperature set-points on July 1, 2010

Sustainability Performance Simulation Tools for Building Design. Table 10 Comparison of cooling energy consumption and number of hours when temperature set-points are not met

Energy consumption (kWh)		Energy saving (%)
Scheduled temperature set-points	96.83	
NMPC optimization	76.92	17.8
Simulated NMPC optimization with reduced infiltration	77.3	20.2
Temperature set-point not met while occupied (h)		*Improved set-point met time (%)*
Scheduled temperature set-points	3	
NMPC optimization	2	33%
Simulated NMPC optimization with reduced infiltration	1	66%

In summary, it can be seen that NMPC-based control of HVAC systems is an active "self-learning" process compared to the passive conventional HVAC system which only responds to a rigid predetermined indoor set-point temperature schedule. The integrated HVAC control can dynamically predict the control profile and state variables (e.g., indoor air temperature) based on information derived from the validated building HVAC and weather forecasting models. With the predicted information, the energy consumption of HVAC system can be optimized. Furthermore, the real-time occupant behavior patterns are integrated with the HVAC controls. Hence, when the space is unoccupied, there is no need to maintain the conventional temperature set-point. In addition, the operation of HVAC at night is also integrated with the prediction of occupants' arrival time on the next day. The ventilation rate can be adjusted according to the number of occupants in the space. Such control can operate the HVAC system dynamically and result in energy saving while maintaining desirable set-point temperature as well as indoor air quality. The new features of this integrated HVAC control contribute to the next generation of building energy management systems in both residential and commercial buildings.

Conclusion and Future Trends

Future trends in the development and application of simulation tools will continue to be driven by the needs for knowledge-based design decisions, as demanded by knowledgeable clients, and better quality assurance of the performance assessments. Multidisciplinary teamwork that draws upon relevant expertise across geographical boundaries and the adoption of integrative design approaches to achieve high-performance buildings will be critical factors of success in the design and construction business, particularly in an increasingly global and competitive world market.

The potential use of contemporary information technology (e.g., for architectural and engineering design) in the building industry is extensive, and so are the potential performance benefits and cost savings through more efficient and productive processes. However, all the sophisticated IT in the world will not guarantee a decisive transformation of the industry if it is not accompanied by a new level of commitment from players in the industry. The ultimate key to the successful exploitation of IT is "professionalism" and "discipline" in the way our business is conducted in the building industry to create a high-quality and sustainable living environment.

Meanwhile, the capabilities of simulation tools will continue to evolve to address, among others, two major objectives: Firstly to make simulation tools more accessible to the architectural profession to support the open-ended nature of design inquiry, and secondly, to enable effective "real-time" sharing of design information between the entire team through a web-based infrastructure. The pervasive use of these tools will ultimately depend on how they can effectively support the design decision-making process (providing a level of confidence on the predicted performance of the solution) while reducing project overheads such as time, manpower, training, and computational resources typically associated with advanced performance simulations. If a model is carefully created with high fidelity and solidly based on first-principle physical constructs, which are available in some advanced simulation tools, there can be a significant return on upfront time investment by deploying the same model continuously during the operational phase of the building as part of the integrated building management of control system.

As a collaborative activity, the building delivery process relies heavily on the effectiveness of communication structures and means. While it was initially expected that the application of innovative information technologies would qualitatively enhance the information transfer mechanisms within this process, this has not occurred, at least not to the desired extent. To facilitate better understanding of this evolving circumstance, continuous critical review of the status quo and thoughtful theoretical reflections on the complex relations between process evolution and tool development is necessary.

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Sustainable and Healthy Built Environment

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Article Outline

Glossary

BIDS™ The Building Investment Decision Support tool developed by the Center for Building Performance at Carnegie Mellon University to both assemble research from around the world linking design decisions to performance outcomes and to create a “triple bottom line” calculator to support changes in design decision making.

Biophilia Introduced by E.O. Wilson, the biophilia hypothesis suggests that there is an instinctive bond between human beings and other living systems that must be met by buildings that ensure critical connections.

Cornell medical index An index and questionnaire created by Cornell in 1949 to consistently collect the breadth of pertinent medical and psychiatric data on patients given limited physician time.

Epidemiological case studies Quantitative studies of a group of individuals in controlled environmental conditions with controlled changes in those conditions – interventions that may be evident, blind or double blind – with statistical analysis to demonstrate linkages between the physical environment and outcomes.

Evidenced-based design Use of laboratory and field gathered evidence in design decision making. Evidenced-based design was adopted by the Center for Health Design to improve patient health and safety outcomes through improvements in design.

LEED™, BREEAM™, Greenstar™, CASBEE™ Rigorous, voluntary sustainability standards developed in the USA, UK, Australia, and Japan, respectively, that span land use and site, energy and atmosphere, water, materials and resources, and indoor environmental quality goals.

Mixed mode or hybrid HVAC An approach to space conditioning that combines natural ventilation from operable windows or vents with mechanical heating, cooling, and ventilation systems (HVAC).

Precautionary principle Adopted by the European Community and several nations around the world, the precautionary principle argues that if an action or policy has a suspected risk of causing harm to the public or to the environment, even in the absence of scientific consensus that the action or policy is harmful, the burden of proof that it is not harmful falls on those taking the action.

Triple bottom line Expanding the criteria for evaluating a project’s success from economic benefits alone to include ecological and social cost benefits, adopted by the United Nations and others to ensure public sector decision making reflects full cost accounting, and colloquialized as “people, planet, and profit.”

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Definition of the Subject

While sustainable design is focused on reducing the environmental footprint, the resources consumed, and the waste produced, it is also critically linked to our health. Design decision making for sustainability – land use, building massing and enclosure, lighting systems, mechanical systems, interior systems, building operation and management – can not only reduce our environmental footprint, it can and must enhance our visual, aural, dermal, musculoskeletal, circulatory, respiratory, reproductive, and mental health. The challenge is to explore the linkages between critical design decisions, from land use to material and system design to building maintenance and operations, to critical health outcomes. Based on years of gathering emerging laboratory, field, and epidemiological case studies, the Center for Building Performance and Diagnostics at Carnegie Mellon University has been assembling the research on environmental, health, and productivity benefits of the range of high-performance building systems that are the basis for sustainable design. Captured in a Building Investment Decision Support tool (BIDS™), the cost-benefits of investing in a sustainable built environment revealed in these case studies should drive measurable changes in building design, construction, and management. Given critical data sets linking sustainable design solutions and health, triple bottom line accounting can support strategic, long-term decision making in the built environment, commensurate with its intended life of 30–50 to hundreds of years. At the same time, the funding for ongoing research and the aggregation of knowledge linking health and the built environment within an international data base will be critical to ensuring the necessary investment in the quality of our buildings and communities – the foundation of sustainability.

Introduction: Linking Definitions of Sustainability and Health

Many decision makers assume that sustainable design is about resource conservation – energy, water, and material resources. The last 10 years, however, has seen a dramatic broadening of the definition of sustainability to include commitments to mobility through improvements in land use and transportation, commitments to health and productivity through improvements in indoor environmental quality, and commitments to the protection of regional strengths a more globally shared quality of life is pursued. In the USA, this broader definition of sustainability is most often ensured through the LEED™ standard (Leadership in Energy and Environmental Design) of the US Green Building Council. Paralleled by developments in the UK (BREEAM), Australia (Greenstar), and Japan (CASBEE), the 100 or more credits in the LEED sustainability rating systems for new and existing buildings extend beyond conservation goals for energy, water, and materials, to include sustainable sites and transportation, indoor environmental quality, and regional sustainability (usgbc.org/LEED).

The Center for Building Performance and Diagnostics at Carnegie Mellon University would argue for expanding this definition even further, to give even greater emphasis to contextual and regional design goals, to accessible and flexible infrastructures that support change, to natural/passive conditioning, and to human engagement, motivation, and health. Indeed, the CBPD research team proposes the following definition:

- Sustainable design is the result of a trans-disciplinary, collective design process driven to ensure that the built environment achieves greater levels of ecological balance in new and retrofit construction, toward the long term viability and humanization of architecture. Focusing on environmental context, sustainable design merges the natural, minimum resource conditioning solutions of the past (daylight, solar heat and natural ventilation) with the innovative technologies of the present, into an integrated "intelligent" system that supports individual control with expert negotiation for environmental quality and resource consciousness. Sustainable design rediscovers the social, environmental and technical values of pedestrian, mixed-use communities, fully using existing infrastructures, including "main streets" and small town planning principles, and recapturing indoor-outdoor relationships. Sustainable design avoids the further thinning out of land use, and the dislocated placement of buildings and functions caused by single-use zoning. Sustainable design introduces benign, non-polluting materials and assemblies with lower embodied and operating energy requirements, and higher durability and recyclability. Finally, sustainable design offers architecture of long term value through "forgiving" and modifiable building systems, through life-cycle instead of least-cost investments, and through timeless delight and craftsmanship [44].

The depth of the definition of sustainability matters, especially when assessing the relevance of sustainable design, construction, and operations of buildings for long-term human and environmental health. This chapter explores the range of health outcomes that can be linked to these important principles for the design of a sustainable built environment:

CMU: Seven Principles for the Design of Sustainable Built Environments

1. Sustainable design depends on an integrative, human-ecological design approach.
2. Sustainable design depends on changing approaches to land use and community fabric.
3. Sustainable design depends on the promotion of infrastructures to neighborhood amenities.
4. Sustainable design depends on the effective use of natural, local, and global resources to reduce resource demands and maximize resource use.
5. Sustainable design depends on the design of flexible, forgiving systems.
6. Sustainable design depends on the use of healthy, renewable materials and assemblies.
7. Sustainable design depends on design for life cycle instead of first cost.

A Definition of Health to Be Integral with Sustainable Design

Equally critical to a shared definition of sustainable design is the exploration of a shared definition of human health. Building on the Cornell Medical Index of 1949 [13], the Center for Building Performance at Carnegie Mellon is using the following 10 indices for evaluating the importance of design, construction, and operation decisions on human health:

Ten qualities of human health integral with sustainable design

1. Respiratory health
2. Digestive health
3. Visual health
4. Aural health
5. Skin/dermal health (integumentum system)
6. Musculoskeletal health
7. Circulatory health
8. Nervous system health
9. Genitourinary (including reproductive) health
10. Mental health

To date, evidence from research suggests six primary clusters of health issues related to the built environment: respiratory (chest, wheeze, allergies, asthma, colds, flu), mucosal (eye, nose, throat), dermal (face, hand skin); neurological (e.g., headache, migraine, dizziness, heavy-headedness), musculoskeletal (to include body mass today), and mental health.

The challenge is to definitively link these health issues to the quality of the built environment. Given the unbounded variations in physical settings and their management over time, arguments for causality between a single design decision, such as type of ventilation system, and health outcome will be very difficult. Moreover, funding for these multivariate research questions is scarce. The challenge is to identify the controlled experiments, field intervention studies, and portfolio wide studies that might support effective design decision making for sustainability. The Center for Health Design (http://www.healthdesign.org/) has made the case for evidenced-based design that "is the process of basing decisions about the built environment on credible research to achieve the best possible outcomes." They have launched the "Pebble Project" to capture profiles of healthcare organizations whose facility design has made a difference in the quality of care – as well as their financial performance. These case studies explore the potential benefits of daylight and view, acoustics, variations in ventilation, hospital room layout and configuration, and more, on hospital outcomes. These projects are changing design practice, but some might argue they are not based on definitive research finding that can explain the mechanisms whereby health outcomes are improved. For this to occur, multiyear epidemiological studies as well as controlled laboratory and field experiments must be undertaken by collaborative teams of health and building professionals. In the meantime, the design community is making decisions every day that can positively or negatively impact human health. To this community, it is argued that every study available must contribute to informed decision making, and every act must be based on the European Union's precautionary principle:

- Where there is uncertainty as to the existence or extent of risks of serious or irreversible damage to the environment, or injury to human health, adequate protective measures must be taken without having to wait until the reality and seriousness of those risks become fully apparent.

  http://www.sustainable-design.ie/arch/precautionaryprinciple.htm.

The precautionary principle argues for the building community to take responsibility to protect the public from exposure to harm, whenever scientific investigation has found a plausible risk. These protections can be relaxed only if further scientific findings emerge that provide sound evidence that no harm will result. For example, scientific investigation suggests that outdoor air ventilation rates should be doubled in buildings to reduce the risks of colds, flus, and respiratory illnesses. Research further argues that these increased ventilation rates should be accompanied by economizer cycles and/or heat recovery to ensure that primary energy loads will not increase, since power plant pollution also poses measurable health risks. The following sections will elaborate on the sustainable building design decisions for which scientific evidence is emerging, but not yet definitive given our weak commitment to funding research on health and the built environment.

Linking Health and the Built Environment

By setting a definition of the attributes of sustainable design against the characteristics of human health, even intuitive judgment would illuminate the importance of building design, construction, and operation for human health (Fig. 1).

With over 10 years of intense study by faculty, researchers, and graduate students, the Center for Building Performance and Diagnostics at Carnegie Mellon have been collecting building case studies as well as laboratory and simulation studies in an effort to statistically link the quality of buildings – system by system – to productivity, health, and life cycle sustainability.

Amassed in the BIDS™ (Building Investment Decision Support) tool, these case studies enable building decision makers to calculate return on investments for high-performance building components and systems, and will lead to greater understandings of the importance of buildings and communities to human health (see http://cbpd.arc.cmu.edu/bidstrial). The following six sections explore design innovations and the potential health impacts of changes in land use, building massing and enclosure, HVAC engineering, daylight and lighting system design, interior systems, and long-term building maintenance and operations.

Sustainable Land Use and Health

One of the most significant design shifts needed for the long-term health of humans is to move away from the automobile-centric land-use planning that makes pedestrian lifestyles impossible. The dramatic reductions in walking and biking that have resulted from sprawl and single-use zoning have contributed to increasing rates of obesity in industrialized nations [10, 20, 26, 55]. At the same time, the increased reliance upon automobiles has resulted in ever-increasing levels of particulate and ozone levels that are respiratory and cardiovascular hazards [24]. David L. Skole of the Center for Global Change and Earth Observations at Michigan State University identifies a range of health effects from sprawl: air pollution, CO_2 emissions, heat island effect, reduced physical exercise, increased car accidents, and pedestrian injuries, as well as declining water quality [58].

Numerous studies have revealed the seriousness of particulate-related health concerns. Wordley et al. [75] identified a 2.4% increase in respiratory hospital admissions and a 2.1% increase in cerebrovascular admissions associated with a 10 $\mu g/m^3$ increase in PM10 in the air, which, according to Dockery & Pope [15], increases respiratory admissions by 0.8 $\sim$ 3.4%. Tenias et al. [64] found that a 10 $\mu g/m^3$ increase of NO_2 and O_3 in the air causes increases in the number of

	Respiratory system	Digestive system	Eyes, vision, circadian system	Ears, hearing, concentration	Skin	Musculo-skeletal	Circulatory system	Nervous system	Genitourinary system	Mental health, stress, biophilia
Land use										
Design live - work - walk communities		●				●	●			
Design mixed mode mobility	●	●				●	●			
Increase landscape/reduce paving	●					●		●		●
Distributed/ renewable power sources	●									
Building Massing and Enclosure										
Design for Daylighting/View /Passive Solar			●					●		●
Design for Natural Ventilation	●									●
Engineer Thermal Load Balancing							●			
Design Enclosure Integrity	●			●			●			
Lighting and HVAC Systems										
Separate ambient and task lighting			●							
Specify high performance lighting & controls			●							
Separate ventilation & thermal conditioning	●						●			●
Increase outside air & ventilation effectiveness	●									
Engineer moisture humidity management	●				●					
Engineer individual control of temperature							●			
Interior Systems										
Specify ergonomic furniture						●	●			
Design spatial layout/density for health/safety						●				
Specify acoustic quality				●						
Specify materials vs. out gassing/ degradation	●							●		
Specify materials vs. irritation/ re-infection	●	●			●					
Specify materials vs. mold	●									
Operations										
Continuously Commission Systems	●									
Eliminate standing water, dampness & mold	●									
Design for non toxic pest/plant management	●	●						●		
Design for environmentally benign cleaning	●				●			●		
Improve food/vending quality for health		●								
Improve water quality for health		●								
Reduce waste/ manage waste vs. pests	●									●

Sustainable and Healthy Built Environment. Figure 1
Correlating decision making in the built environment to improving human health should be a major international initiative

emergency visits for asthma by 7.6% and 6.3%, respectively.

Moreover, automobile-centric land use and single-use zoning has led to increasing inactivity in children, teens, and senior citizens that contributes to obesity and all the associated health impacts of obesity, as well as potentially contributing to attention deficit and depression. In a 2004 cross-sectional survey of 10,878 adults from the Atlanta, Georgia region, Frank et al. identify a 12.2% decline in the likelihood of obesity for each quartile increase in land use mix, which was defined on a scale from 0 (indicating a single-use environment) to 1 (indicating a perfectly equal mix of residential, commercial, office, and institutional uses). They also found a significant relationship between reductions in vehicle miles travel and reductions in particulate matter, NOX and VOC pollution, which have other health ramifications (see Fig. 2, [23]).

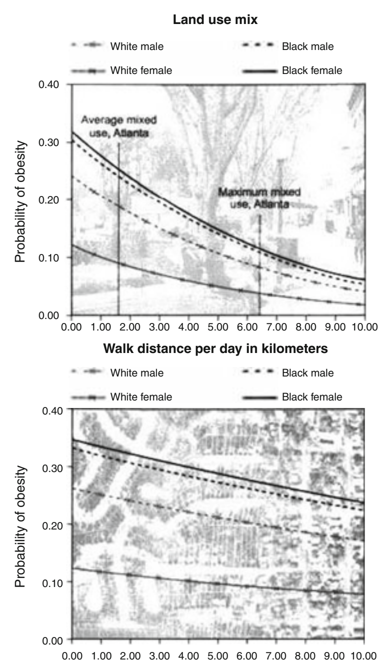
The US studies on land use and obesity are summarized and advanced in the 2006 National Institute of Health study of the "Relationship Between Urban Sprawl and Weight of United States Youth" [21]. "The first studies reporting a direct relationship between the built environment and obesity were published in 2003 [10, 19, 26, 55]. After controlling for age, education, fruit and vegetable consumption, and other socio-demographic and behavioral covariates, Ewing et al. [20] found that adults living in sprawling counties had higher body mass indices (BMIs) and were more likely to be obese (BMI $\geq$ 30) than were their counterparts living in compact counties. Independent studies have since generally confirmed these original findings. Specifically, all macro-level (county or larger) studies, and all but one micro-level (neighborhood) studies, have found significant relationships, in the expected direction, between sprawl-like development patterns

Increased density + mixed land use = Health

Frank et al 2004

In a 2004 cross-sectional survey of 10,878 adults from the atlanta, Georgia region, Frank et al identify a 12.2% decline in the likelihood of obesity for each quartile increase in land use mix, which was defined on a scale from 0 (indicating a single-use environment) to 1 (indicating a perfectly equal mix of residential, commercial, office, and institutional uses).

First cost savings:	$4,408 / person
Annual health savings:	$51 / person
RoI:	Immediate



Reference: D. Frank, M. Andresen, T. Schmid. Obesity relationships with community design, physical activity, and time spent in cars. American Journal of Preventive Medicine, Volume 27, Issue 2, August 2004.

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Sustainable and Healthy Built Environment. Figure 2
Land use can significantly reduce vehicle miles traveled which in turn reduces the pollution that causes growing respiratory health concerns

and BMI, after controlling for socio-demographic and other influences" [21].

Moreover, automobile-based design is "paving" the countryside, with the elimination of landscapes that act as natural lungs for filtering our air, and with the increasing salts, oils, and storm-sewer overflows that result in toxic runoff into our drinking water. The quantification of these serious health hazards should fully justify the shift in sustainable design to: live-work-walk lifestyles with mixed-use communities; multigenerational mobility with mixed mode transportation; and the preservation and celebration of natural landscapes and sustainable infrastructures.

Guidelines Linking Sustainable Land Use and Health
Design live-work-walk communities to reduce car pollution – particulates and ozone – that trigger asthma
Design for pedestrian, bicycle, transit mobility to reduce obesity
Minimize paving for roads and parking to reduce salting and oil runoff, as well as standing water concerns
Design landscape dominant environments to reduce thermal heat islands, heat stress, and rebuild nature's lungs for air quality

Sustainable Building Massing/Enclosure and Health

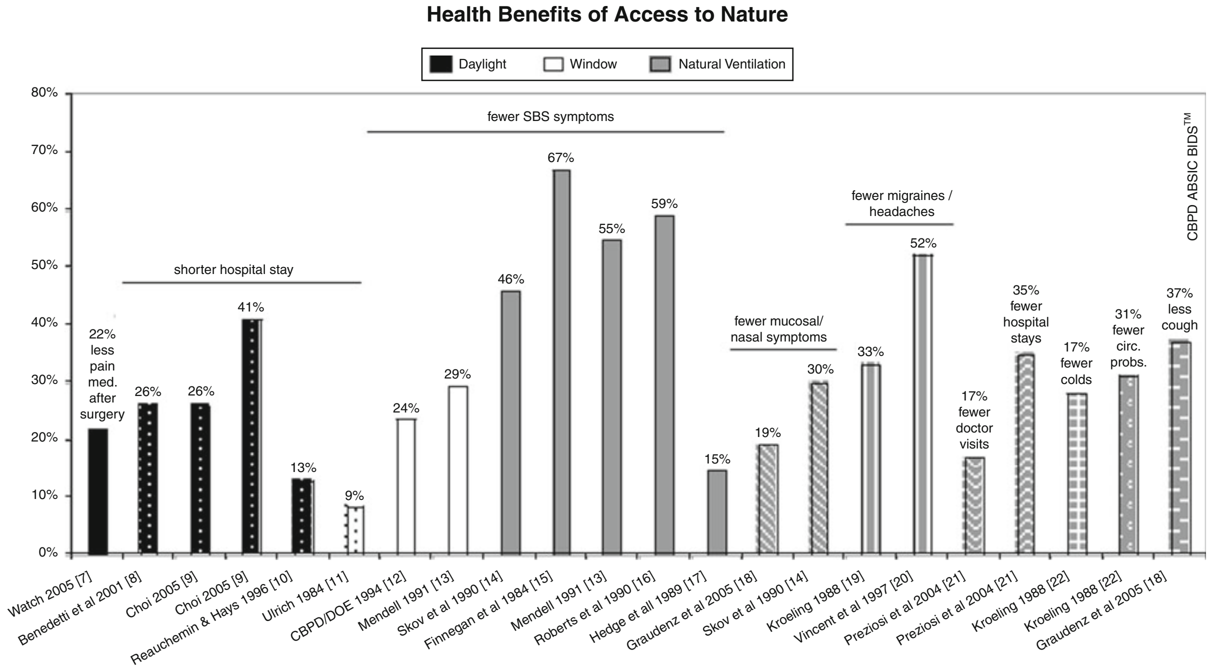
After land use design, the second most critical design decision for human health might be building massing and enclosure specifications. On the one hand, access to nature's assets – daylight, natural ventilation, natural comfort and thermal variation, views and physical access to outdoor activity - are becoming increasingly linked to human health. On the other hand, humans need protection from nature's liabilities – overheating, excessive cold, wind, rain, and snow. The design of the building enclosure is critical for managing both these climatic assets and liabilities.

The CBPD has identified a range of international case studies linking access to the natural environment – daylight, views, and natural ventilation – to improved health outcomes, including reductions in headaches, colds, sick building symptoms (SBS), and patient length of stay (see Fig. 3). Beyond the health benefits, a number of international case studies demonstrate that access to the natural environment increases individual productivity between 3% and 18%, reduces absenteeism between 9% and 71%, and offers over 50% lighting and HVAC energy savings (CBPD).

While the debate continues as to the mechanisms by which *daylight* improves health, research continues to reveal that sunlight, especially morning sunlight, reduces length of stay for patients recovering from surgery, bipolar, and SAD treatment [3, 4, 12, 71]. In a 2005 building case study of Inha University Hospital in Korea, Choi identifies a 41% reduction in average length of stay among gynecology patients in bright (sunlit) rooms, as compared to those in dull rooms, in spring, and an average 26% reduction in average length of stay among surgery ward patients in bright rooms, as compared to those in dull rooms, during spring and fall [12]. In a separate study of pain medication use among 89 patients undergoing elective cervical and lumbar spinal surgery at Montefiore Hospital in Pittsburgh, PA, Walch et al. identify a 22% reduction in analgesic medication use among patients in bright rooms who were exposed to more natural sunlight after surgery, as compared to patients located in dim rooms after surgery [71] (Fig. 4).

The work of the Lighting Research Institute at RPI has begun to reveal the possible mechanisms of these health outcomes, identifying the relationship of ultraviolet light exposure to the production of melatonin, a natural hormone that controls circadian rhythms that are related to sleep cycles and potentially to reduced cancer cell development [7]. At the same time daylight, and most especially sunlight, can introduce glare and overheating that might negatively affect human health outcomes.

The importance of *views* of nature and proximity to windows for human health is equally important for study, with the work of Ulrich [68], Mendell [45], Heschong Mahone Group [31] now Kellert [41] identifying possible links between views and reduced length of hospital stay after surgery, reduced sick building syndrome, improved overall emotional health, and improved performance at task. In a 1991 11-building study of office buildings in San Francisco, Mendell [45] identifies 25–52% reductions in reported SBS symptoms among occupants located within 15 ft of



Sustainable and Healthy Built Environment. Figure 3

A range of international case studies link access to the natural environment – daylight, views, and natural ventilation to improved health outcomes – reductions in headaches, colds, sick building symptoms (SBS), and patient length of stay

a window, as compared to those seated further from a window.

In addition to confirming the importance of seated views for all building occupants, research is critically needed to understand the importance of the content of those views from windows for human health (e.g., the benefit of landscape views over parking lots, building walls, and sky). In a seminal 1984 field study at a Pennsylvania hospital, Ulrich [68] identifies an 8.5% reduction in postoperative hospital stay (8.7 vs. 7.96 days) for gall bladder surgery patients who had a view of a natural scene from their hospital room, as compared to those with a view of the brick wall of the adjacent building wing. Patients with a view of nature also received fewer negative evaluations from nurses and took fewer strong analgesics (see Fig. 5).

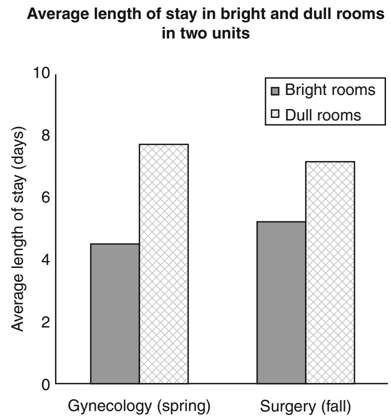
In addition to sunlight and views, it is critical to understand the benefits of direct access to outdoor air and outdoor spaces through operable windows and doors. The value of increasing outside air delivery rates is becoming increasingly evident, as will be described in the section on HVAC design. It is not clear, however, whether increased levels of outside air are more effectively delivered through *natural ventilation* (operable windows) or through mechanical systems that incorporate filtration, dehumidification, and thermal conditioning of that outside air. There are over a dozen studies that reveal the benefits of natural ventilation in existing buildings as compared to mechanically ventilated buildings – benefits that range from reduced headaches, mucosal symptoms, colds, coughs and circulatory problems, to reduced SBS symptoms. In a 1992 study of two London hospitals, Kelland [40] identifies a 40% reduction in sick building syndrome (SBS) symptoms among staff of a naturally ventilated hospital, as compared to those of a mechanically ventilated hospital (see Fig. 6). In a 2004 multiple building study of professional middle-aged women in France, Preziosi et al. [52] identify a 57.1% reduction in sickness absence, a 16.7% reduction in medical services use (doctor visits), and a 34.8% reduction in hospital stays

Daylight = Health

Inha University Hospital / Choi 2005 (Hospital)

In a 2005 building case study of Inha University Hospital in Korea, Choi identifies a 41% reduction in average length of stay among gynecology patients in bright (sunlit) rooms, as compared to those in dull rooms, in spring, and an average 26% reduction in average length of stay among surgery ward patients in bright rooms, as compared to those in dull rooms, during spring and fall.

First cost increase:	$ 1,000 / bed
Annual health savings:	$ 10,115 / bed
ROI:	**1,011%**



Reference: Choi, Joonho. (2005). Study of the Relationship between Indoor daylight Environments and Patient Average Length of Stay (ALOS) in Healthcare Facilities, Unpublished master's thesis, Department of Architecture, Texas A&M University. College Station, TX.

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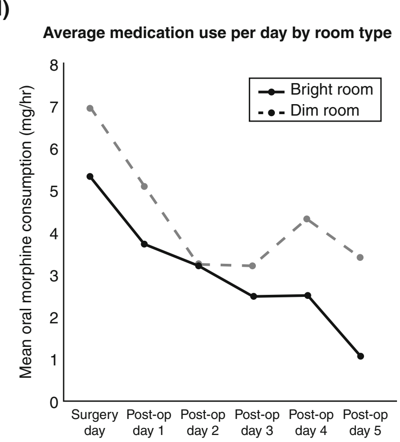
Daylight = Health

Montefiore Hospital / Walch et al 2005 (Hospital)

In a 2005 study of pain medication use among 89 patients undergoing elective cervical and lumbar spinal surgery at Montefiore Hospital in Pittsburgh, PA, Walch et al identify a 22% reduction in analgesic medication use among patients in bright rooms who were exposed to more natural sunlight after surgery, as compared to patients located in dim rooms after surgery.

First cost increase:	$ 1,000 / bed
Annual health savings:	$ 28 / bed
ROI:	**3%**



Reference: Walch JM, Rabin BS, Day R, Williams JN, Choi K, Kang JD (2005) The effect of sunlight on postoperative analgesic medication use: a prospective study of patients undergoing spinal surgery. Psychosom Med 67:156–163

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Sustainable and Healthy Built Environment. Figure 4
In extensive hospital record studies, Choi and Walch identified the value of southern and south eastern rooms to reduced patient length of stay

among subjects with natural ventilation in their workplace, as compared to those with air conditioning (see Fig. 6). In a 2007 study of 104 child care centers in Singapore, Zuraimi et al. identifies a 10.7% decrease in cough with cold/flu symptoms, a 31% decrease in phlegm with cold/flu, a 27.3% decrease in coughing attacks lasting more than 1 week, and a 33.3% decrease in lower respiratory illness in children attending naturally ventilated child care centers as opposed to centers with hybrid ventilation [77].

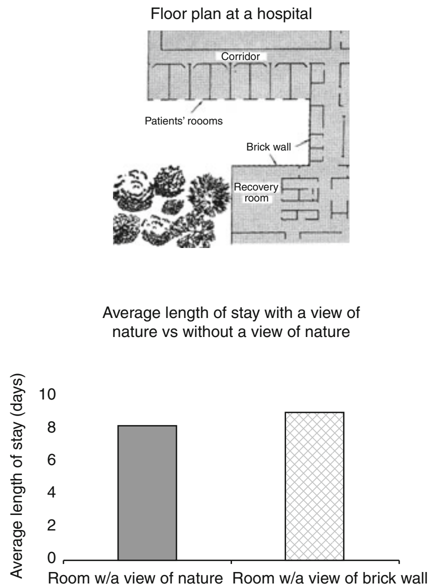
While operable windows can bring in higher quantities of outside air, they can also bring in unwanted outdoor pollution, humidity, rain, and noise. The pros and cons of increasing outside air rates through natural

Seated Access to Views = Health

PA Hospital / Ulrich 1984

In a 1984 observational field study at a Pennsylvania hospital, Uirich identifies an 8.5% reduction in post-operative hospital stay (8.7 vs 7.96 days) for gall bladder surgery patients who had a view of a natural scene from their hospital room, as compared to those with a view of a brick wall. Patients with a view of nature also received fewer negative evaluations from nurses and took fewer strong analgesics.

First cost increase:	$ 5,000 / bed
Annual health savings:	$ 2,237 / bed
ROI:	**45%**



Reference: Ulrich, R. (1984) View Through a Window May Influence Recovery From Surgery. Science, 224(4647), pp. 420-421.

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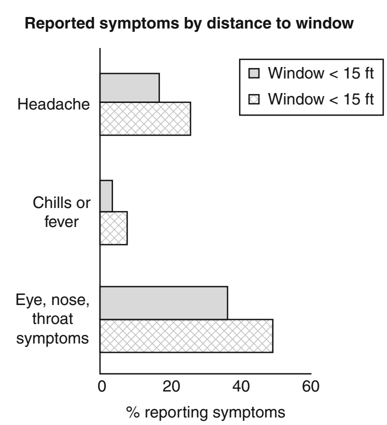
Seated Access to Windows = Health + Individual Productivity

CA Healthy Building Study / Mendell 1991 (Wargocki et al 2000)

In a 1991 multiple building study of 11 office buildings in San Francisco, Mendell identifies 25% - 52% reductions in reported SBS symptoms among occupants located within 15 feet of a window, as compared to those seated further from a window.

In a 2000 study, Wargocki et al identify a 1.1% productivity increase for every 10% reduction in SBS complaints, suggesting an average 4.3% productivity gain for workers seated near a window.

First cost increase:	$1,000 / employee
Annual productivity savings:	$1,935 / employee
Annual health savings:	$40
ROI:	**198%**



Reference: Mendell, Mark J. (1991) Risk Factors for work-Related Symptoms in Northern California Office Workers. Wargocki, P, Wyon, D, and Fanger, P.O. (2000) Pollution Source Control and Ventilation Improve Heath, Comfort and Productivity. In Proceedings of Cold Climate HVAC 2000, Sapporo, Japan, November 1-3, 2000, pp. 445-450.

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Sustainable and Healthy Built Environment. Figure 5
Ulrich and Mendell identified the importance of views and view content to sick building syndrome and reduced patient length of stay

versus mechanical means are outlined in Fig. 3, with a bias to the value of natural ventilation, especially given the variable long-term performance of HVAC systems and controls in operation (Fig. 7).

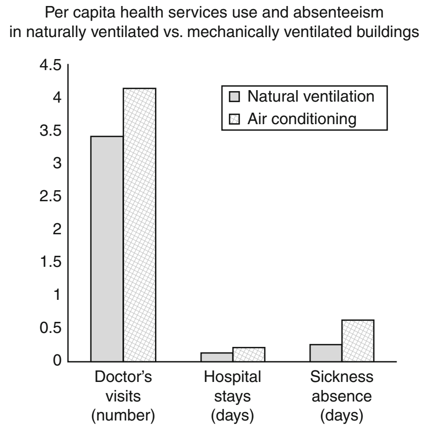
The design decisions central to ensuring daylight, view, and natural ventilation include increasing surface area with thinner floor plates and resolving glare, overheating, heat loss, and rain penetration through

Natural Ventilation = Health + Individual Productivity

Preziosi et al 2004

In a 2004 multiple building study of professional middle-aged women in France, Preziosi et al identify a 57.1% reduction in sickness absence, a 16.7% reduction in medical services use (doctor visits), and a 34.8% reduction in hospital stays among subjects with natural ventilation in their workplace, as compared to those with air conditioning.

First cost increase:	$1,000 / employee
Annual health savings:	$181 / employee
Annual productivity savings:	$85 / employee
ROI:	**27%**



Reference: Preziosi P., S. Czerniichow, P. Gehanne, and S. Hercberg (2004) Workplace air-conditioning and health services attendance among French middle-aged women: a prospective cohort study. International Journal of Epidemiology, 33(5), pp. 1120-1123.

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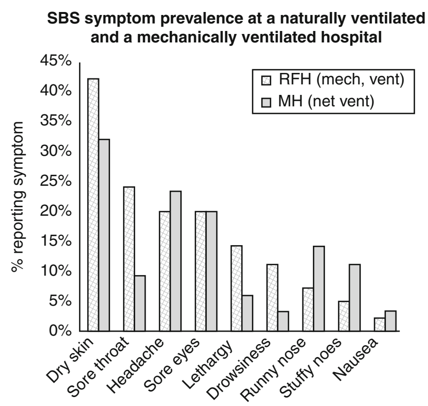
Natural Ventilation = Health

London Hospitals / Kelland 1992 (Wargocki et al 2000)

In a 1992 multiple building study of two London hospitals, Kelland identifies a 40% reduction in sick building syndrome (SBS) symptoms among staff of a naturally ventilated hospital, as compared to those of a mechanically ventilated hospital.

In a 2000 study, Wargocki et al identify a 1.1% increase in productivity for every 10% reduction in SBS complaints, suggesting a 4.4% productivity gain due to natural ventilation.

First cost increase:	$543 / employee
Annual productivity savings:	$1,980 / employee
ROI:	**365%**



Reference: Kelland, P (1992) Sick Building Syndrome, Working Environments and Hospital Staff. Indoor Environment, v1, PP. 335-340; Wargocki, P, Wyon, D, and Fanger, P. O. (2000) Pollution Source Control and Ventilation Improve Health, Comfort and Productivity. In Proceedings of Cold Climate HVAC 2000, Sapporo, Japan, November 1-3 2000, pp. 445-450.

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Sustainable and Healthy Built Environment. Figure 6

Kelland identified a reduction in hospital staff SBS and Preziosi identified reductions in absenteeism and doctor visits in buildings with natural ventilation as compared to those with mechanical ventilation

appropriate enclosure design. In some respects, sustainable, healthy buildings have many of the characteristics of sustainable, healthy humans – they are physically fit rather than obese (thin floor plans, finger plans, and courtyard buildings); they have circulatory systems that take the heat from the core out to the surface (through water mullions or air flow windows described in Chap. 2); and they absorb sunlight and breathe fresh air. At the same time, sustainable buildings are designed to reduce or make use of climatic liabilities – rain, cold and hot

Should Windows Open?

No	Yes
Avoid outdoor pollution	Dilute indoor pollution from HVAC sources
	Dilute indoor pollution from materials/ activities
Avoid outdoor humidity	Diffuse indoor humidity build up
Avoid outdoor noise (traffic, HVAC, mowers)	Connect to nature – air, sounds
Well designed/maintained HVAC ensures temperature control and ventilation rates	Increase local ventilation rates as needed
	Increase local thermal control in cool periods
Avoid rain penetration	Design windows to shed rain

Sustainable and Healthy Built Environment. Figure 7
Operable windows are critical to long term sustainability and human health, so challenges should be addressed through design

temperatures, diurnal temperature swings, excessive sun, freeze-thaw – with completely regional design solutions.

Guidelines Linking Sustainable Building Massing/Enclosure and Health
Design for daylighting without glare to support visual acuity and reduce headaches
Design for natural ventilation without drafts and rain penetration to reduce respiratory symptoms
Engineer thermal load balancing to eliminate radiant asymmetry associated with arthritis and circulatory disorders
Design for passive solar heating where climate appropriate for thermal comfort and UV benefits
Design enclosure integrity to eliminate mold affecting SBS, respiratory/allergy and asthma

Sustainable HVAC and Health

The design of heating, ventilation, and air conditioning systems (HVAC) for human health are based on at least three improvements in individual occupant conditions: increased outside air rates and filtration; improved moisture/humidity control; and improved thermal comfort control.

In addition to managing sources of pollution, healthy indoor air is dependent on a commitment to improving the quality and quantity of outside air. Increasing outside ventilation rates for health has substantial research justification – a doubling or tripling of code requirements for outside air measurably reduces headaches, colds, flus, nasal symptoms, coughs, and SBS symptoms [5, 6, 16, 22, 34, 47, 49, 59, 62, 65]. Increasing outside air rates without energy penalty may be achieved by maximizing natural ventilation with mixed-mode HVAC systems that support natural ventilation; by designing HVAC systems with *separate* ventilation air and thermal conditioning systems, which permits thermal conditioning to be water or air based; or at a minimum by increasing outside air quantities with effective filtration and heat recovery for energy efficiency. In a meta-analysis of 20 ventilation rate studies, Seppanen, Fisk, and Mendell found that the relative risks of respiratory illnesses were 1.5–2 higher in low ventilation rate buildings (below 10 L/s/person) as compared to high ventilation rate buildings (up to 20 L/s/person), alongside a 1.1–6 higher risk of sick building syndrome symptoms in low ventilation rate buildings [56].

A recent international study of papers published in peer-reviewed scientific journals identified a "biological plausibility for an association of health outcomes with ventilation rates, although the literature does not provide clear evidence on particular agent(s) for the effects. Higher ventilation rates in offices, up to about 25 L/s per person, are associated with reduced prevalence of sick building syndrome (SBS) symptoms. The limited available data suggest that inflammation, respiratory infections, asthma symptoms, and short-term sick leave increase with lower ventilation rates. Home ventilation rates above 0.5 air changes per hour (h^{-1}) have been associated with a reduced risk of allergic manifestations among children in a Nordic climate. The need remains for more studies of the relationship between ventilation rates and health, especially in diverse climates, in locations with polluted outdoor air and in buildings other than offices [61]."

To ensure ventilation effectiveness, the ventilation system must be designed to provide air *to the individual* with "task" air systems, ideally with some level of individual control to address local pollutant buildup. In a 2000 building intervention study in 39 Swedish schools, Smedje and Norback identify a 69% reduction in the 2-year incidence of asthma among students in schools that received a new displacement ventilation system with increased fresh air supply rates, as compared to students in schools that did not receive a new ventilation system (see Fig. 8, [59]). In a 2002 controlled experiment, Kaczmarczyk et al. identify a 23.5% reduction in headache symptoms when workers are provided with individually controlled task air systems supplying outdoor air, as compared to a conventional mixing ventilation system, in a room with a typical office pollutant source [39] (see Fig. 8). Both of these studies reveal the health benefits of ensuring that fresh air reaches the nose of every occupant. At the same time, a healthy HVAC system must guarantee outdoor and indoor pollution source control through building design, HVAC configuration, maintenance, and effective filtration. In a 2003 multiple building study of three Montreal office buildings, Menzies et al. identify a 25% reduction in reported mucosal symptoms and a 25% reduction in reported respiratory symptoms due to ultraviolet germicidal irradiation (UVGI) of drip pans and cooling coils within ventilation systems [48]. Additional studies are critically needed to address the importance of both filtration and ongoing HVAC maintenance for human health.

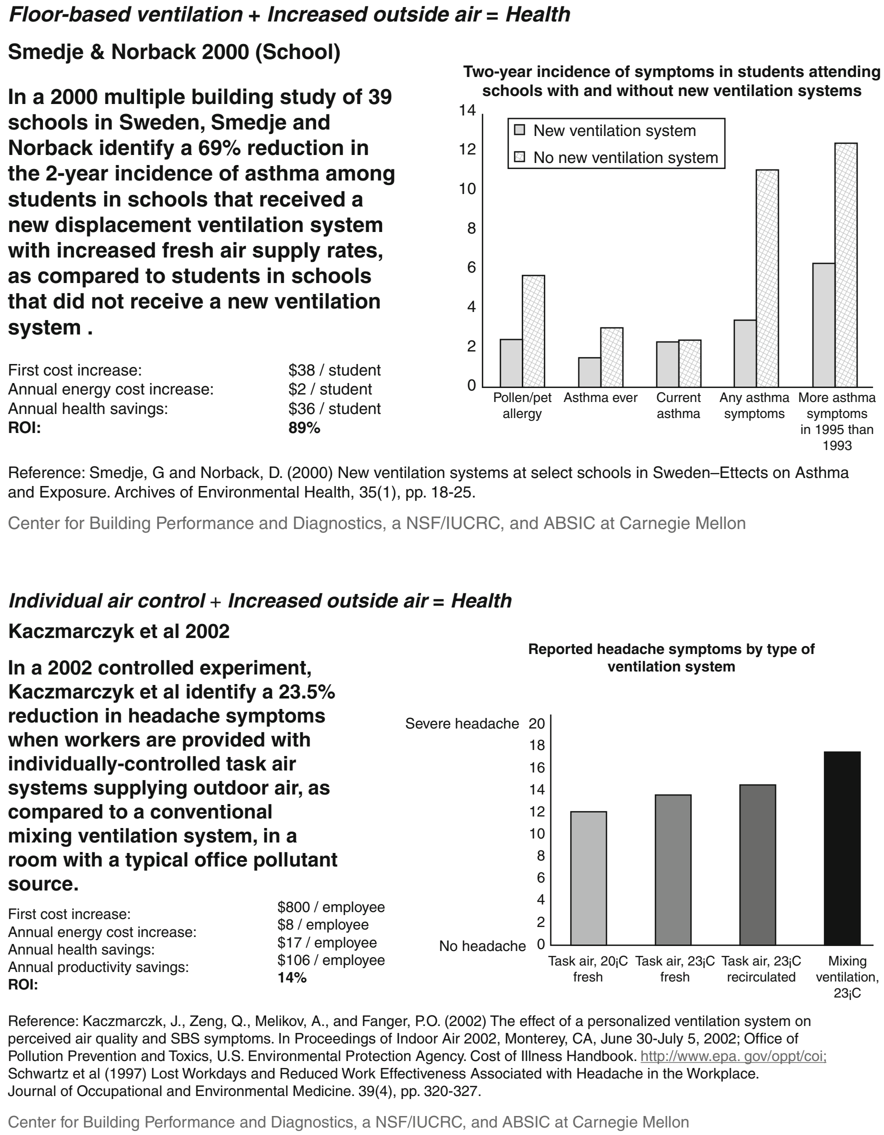
The CBPD has summarized a range of international case studies that link high-performance ventilation strategies to 10–90% reductions in respiratory illnesses, including asthma and allergies, as well as studies that demonstrate reductions in SBS, headaches, flus, and colds (see Fig. 9). In these studies, the critical HVAC improvements are increasing outside air rates, ensuring mold/moisture control and air stream management and maintenance, as well as quality filtration. In addition to health benefits, the CBPD has identified studies that link individual productivity gains of 1.7–11% to high-performance ventilation strategies. Studies also reveal that the energy penalty for increasing outside air rates can be easily eliminated with heat recovery or the use of mixed mode ventilation and conditioning, to generate up to 50–80% energy savings in sustainable HVAC systems (CBPD).

Sustainable HVAC systems must also be designed to provide individual thermal controls. Several laboratory and field experiments link temperature control to individual productivity gains between 0.2% and 7% to 15% energy savings through task thermal conditioning (CBPD), and to reduced headache and SBS symptoms [39, 46]. The challenges for HVAC design for thermal comfort are to design for dynamic thermal zone sizes (anticipating changing density and uses); provide individual thermal controls (through under floor air and task air distribution systems); design for building load balancing and radiant comfort; and finally, to engineer prototyped, robust systems that provide air quality and thermal comfort consistently in the field, over time.

Sustainable HVAC for Health
Increase outside air rates, through natural ventilation or HVAC with heat recovery – to reduce respiratory, allergy, asthma, colds, headaches, SBS
Engineer ventilation effectiveness, including air path and filtration management – to reduce respiratory, throat, and mucosal symptoms
Engineer moisture/humidity management – to reduce mold affecting respiratory illnesses, colds, SBS
Separate ventilation and thermal conditioning systems for individual thermal control – to reduce headaches and SBS symptoms

Sustainable Lighting and Health

Sustainable design must maximize the use of daylight for both sustainability and health, as long as it can be provided without glare and excessive heat loss or heat gain. Daylight can provide the higher light levels needed for fine work, improve color rendition and sculptural definition, give the full spectrum and ultraviolet content that might be critical to circadian rhythms, and provide access to views of nature. Subsequently, electric lighting systems have the responsibility to effectively interface with daylight to meet the needs of specific tasks, and provide the appropriate quantity and quality of light when daylight is not available. To this end, sustainable lighting is dependent on selecting the highest quality

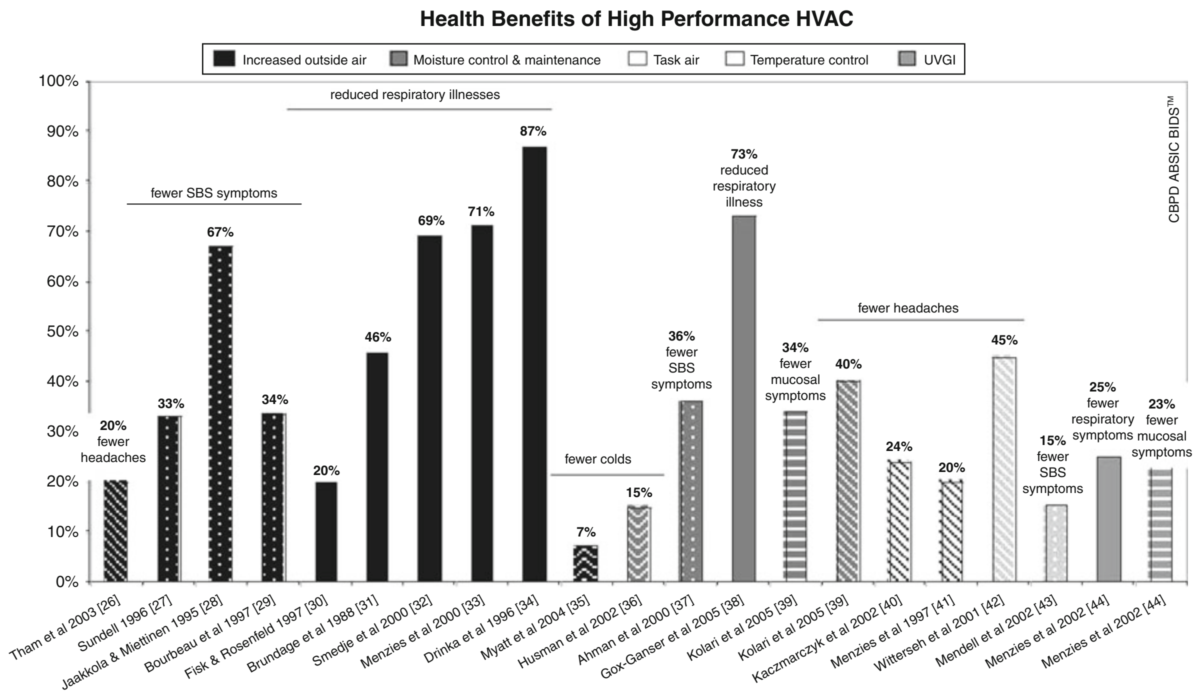


Sustainable and Healthy Built Environment. Figure 8

Smedje and Norback [59] identify a 69% reduction in 2-year incidences of asthma in schoolchildren, and Kaczmarczyk [39] identifies a 23.5% reduction in headache symptoms in offices when ventilation is delivered more effectively to individuals

lighting fixtures, lamps, ballasts, reflectors, lenses, and controls to light each specific task or task surface in an energy-effective manner.

The benefits of well-designed daylight for human health have been previously discussed. If daylight is well designed to control glare and brightness contrast, it is a low energy source that can significantly improve task performance and reduce headaches. In addition, the spectral distribution of daylight, critical to plant health, as well as time-of-day variations in light, may have a measurable impact on our circadian rhythms that impact sleep cycles and energy levels. Finally, as previously discussed, views that may be associated with daylight sources may have a measurable impact on



Sustainable and Healthy Built Environment. Figure 9
A range of international case studies link improvements in HVAC to reduce colds, headaches, respiratory, mucosal, and SBS symptoms

reducing depression and SBS symptoms, while improving hospital recovery rates.

The high-quality lighting fixtures, lamps, ballasts, reflectors, lenses, and controls to light each specific task or task surface also have measurable benefits for human health. For example, in a 1989 controlled field experiment at a government legal office in the UK, Wilkins et al. identify a 74% reduction in the incidence of headaches among office workers when magnetic ballasts are replaced by high-frequency electronic ballasts (see Fig. 10, [74]).

Given the shift from paper-based to computer-based tasks, lighting design must be improved for task performance, for energy effectiveness, and for human health. Sustainable lighting design supports the separation of task and ambient lighting – to enable lower overall ambient light levels at 200–300 lux for computer-based work and face-to-face discussions, to be augmented by higher task light levels at 500–800 lux for fine print work. In a 1998 multiple building study in Germany, Çakir and Çakir identify a 19% reduction in headaches for workers with separate task and ambient lighting, as compared to workers with ceiling-only combined task and ambient lighting (see Fig. 10) [9].

Three international case studies demonstrate that improved lighting design reduces headache symptoms, as shown in Fig. 11. The CBPD has also identified 12 international case studies that indicate that improved lighting design increases individual productivity between 0.7% and 23% while reducing annual energy loads by 27–88% (CBPD).

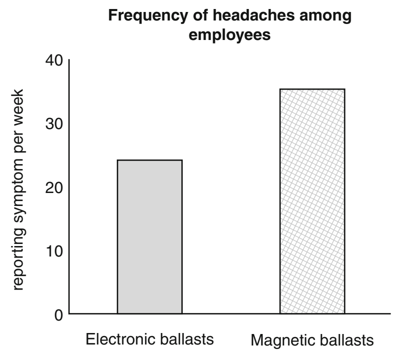
Guidelines for Sustainable Lighting for Health
Design for daylighting without glare to support visual acuity, color rendition, circadian rhythms, view content to reduce headaches, hospital length of stay
Specify high-performance fixtures for maximum lumens/watt, reduced glare, shadowing and noise and to reduce headaches
Separate ambient and task lighting delivery to match light levels to task and provide individual control

High Performance Luminaires = Health

Wilkins et al 1989

In a 1989 controlled filed experiment at a government legal office in the UK, Wilkins et al identify a 74% reduction in the incidence of headaches among office workers when magnetic ballasts are replaced by high frequency electronic ballasts.

First cost increase:	$109 / employee
Annual health savings:	$54 / employee
Annual productivity savings from reduced headaches:	$333 / employee
ROI:	**355%**



Reference: Wilkins, AJ, Nimmo-smith, I, Slater, AI, Bedocs, L. (1989) Fluorescent lighting, headaches and eyestrain. Lighting Research and Technology 21(1), PP. 300-307.

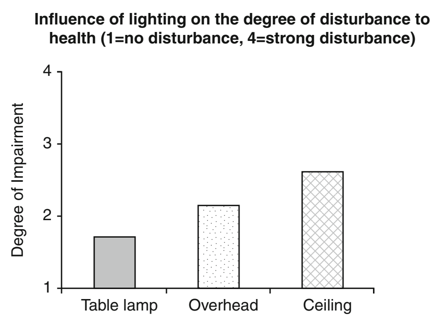
Center for Building Performance and Diagnostics, a NSF/IUCRC, and ABSIC at Carnegie Mellon

Lighting control = Individual productivity + Health

Cakir and Cakir 1998

In a 1998 multiple building study in Germany, Çakir and Çakir identify a 19% reduction in headaches for workers with separate task and ambient lighting, as compared to workers with ceiling-only combined task and ambient lighting.

First cost increase:	$314 / employee
Annual health savings:	$14 / employee
Annual productivity savings:	$87 / employee
ROI:	**32%**



Reference: Cakir, A.E. and Cakir, G. (1998) Light and Health: Influences of Lighting on Health and Well-being of Office and Computer Workers, Ergonomic, Berlin

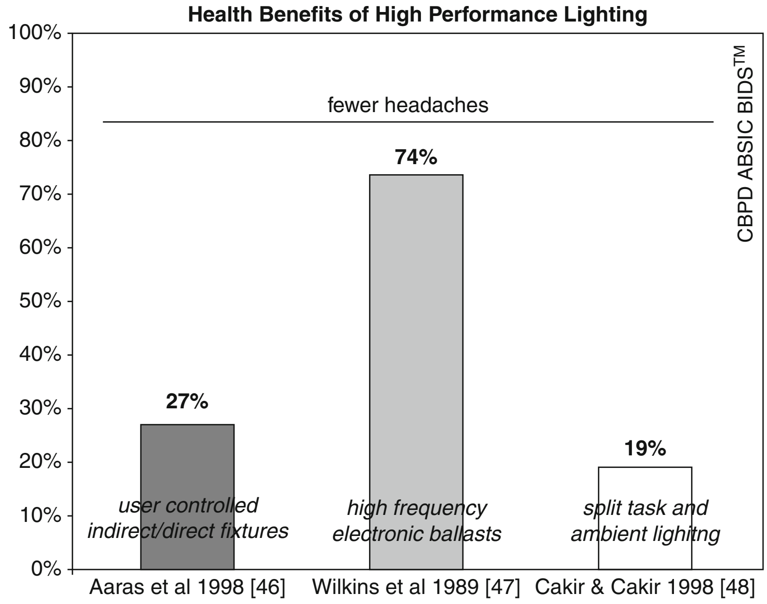
Center for Building Performance and Diagnostics, a NSF/IUCRC, and ABSIC at Carnegie Mellon

Sustainable and Healthy Built Environment. Figure 10
Wilkins identified a 74% reduction in headaches with updated lighting ballasts, and Cakir and Cakir identified 19% reduction in headaches with the separation of ambient and task lighting

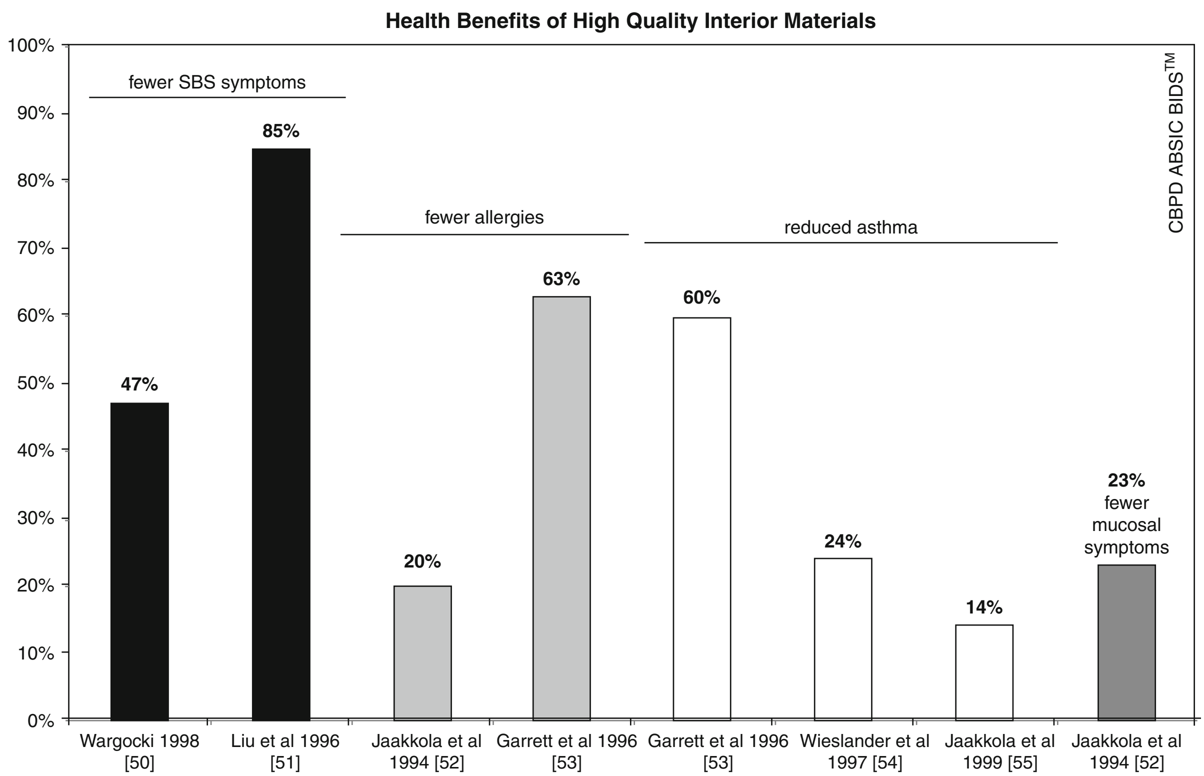
Sustainable Interior Systems and Health: Materials and Ergonomics

Among a range of interior design decisions that affect both sustainability and productivity, at least three design decisions also have measurable health impacts – healthy material selection, acoustic/noise management, and the ergonomics of furniture and space layout.

Interior material selection is critical to thermal performance, air quality (due to outgassing), toxicity in fires, cancer-causing fibers, and mold growth, which in turn impact our respiratory and digestive systems, our eyes and skin. The CBPD has identified six studies linking materials selection to health outcomes including SBS, mucosal irritation, allergies, and asthma (see Fig. 12, [25, 35, 36, 43, 72, 73]). In a 1996 study of 80 homes in Victoria, Australia, Garrett et al. identify a 60% reduction in the prevalence of asthma and a 63% reduction in the prevalence of allergies among children whose homes contain formaldehyde-free composite wood products, as compared to those exposed to formaldehyde from furnishings and products in their



Sustainable and Healthy Built Environment. Figure 11
Case studies link improvements in lighting – ballast quality and individual control – to reduced headache symptoms



Sustainable and Healthy Built Environment. Figure 12
A number of international studies link the quality of building materials and assemblies to allergies, asthma, SBS, and mucosal symptoms

home [25]. While sustainable design depends on the use of materials and assemblies that support healthy indoor environments, it also mandates the selection of materials with low embodied and transportation energy, since these environmental costs carry secondary health concerns.

The most rapidly emerging body of research linking interior materials and health may be related to the infections transferred by contact with surfaces, door handles, faucets, keyboards, telephones, even elevator buttons, and the importance of hands-free design and frequent hand washing. One study by Rheinbaben et al. in a household or dormitory setting, viruses can be transferred to six people successively from contaminated door handles [54]. Contact infection can be addressed through hand washing and green cleaning techniques that are an element in sustainability standards, as well as through hands-free design innovations for shared facilities and equipment.

Managing acoustic quality in indoor environments is critical to both productivity and human health. The importance of reducing unnecessary noise sources while ensuring appropriate sound transmission must continue to be a major requirement for high-performance and sustainable indoor environments. In a 2002 study of ten volunteer teachers from ten randomly selected preschools in Stockholm, Sweden, Sodersten et al. identify an 11% reduction in vocal strain among teachers in classrooms with background noise levels of 55 dB, as compared to those in classrooms with background noise levels of 75.2 dB [60]. Managing unnecessary background noise and ensuring appropriate and necessary sound distribution are as critical to defining indoor environmental quality (IEQ) as visual, thermal, and air quality.

While less tied to today's definition of sustainability, the importance of ergonomic furniture and space configuration for human health must continue to be emphasized in the design of high-performance indoor environments. Given the growing preponderance of computer-based work today, work surfaces, chairs, keyboards, and mouse design must be ergonomically designed to reduce musculoskeletal disorders (MSD). According to a Washington State study, 1.7–3.2% of MSD complaints result in medical costs averaging $22,000 per affected occupant and in many cases permanent consequences for the employee [57]. The CBPD has identified seven international case studies that demonstrate that ergonomic workstations reduce MSD symptoms between 48% and 84% (Fig. 13) [1, 27–29, 32, 69, 76].

Ergonomic design goes beyond anthropometric concerns, however, to also address building layout and densities that support human health and productivity. Jaakkola and Heinonen [33] identified a 35% lower rate of colds among occupants of individual offices, compared to those in shared offices. John Templer [63], the author of a two-volume reference on *Stairs*, carefully illustrates critical design decisions for stairs, ramps, curbs, and surfaces to reduce the frequency of falls, the most frequent cause of injury and death in buildings.

Moving beyond the importance of land use and community design to increase physical activity and health, interior design also plays a major role. An emerging effort in the New York City public health department is the development of design guidelines for new and existing buildings to promote physical activity in an effort to address obesity and its related diseases (http://ddcftp.nyc.gov/adg/downloads/adguidelines.pdf). The *Active Design Guidelines* provides architects and urban designers with a manual of strategies for creating healthier buildings, streets, and urban spaces, based on the latest academic research and best practices in the field. With this addition, the role of interior architecture, engineering, and design on human health is extensive, and suggests a rich mix of critical design guidelines for improved human health over time.

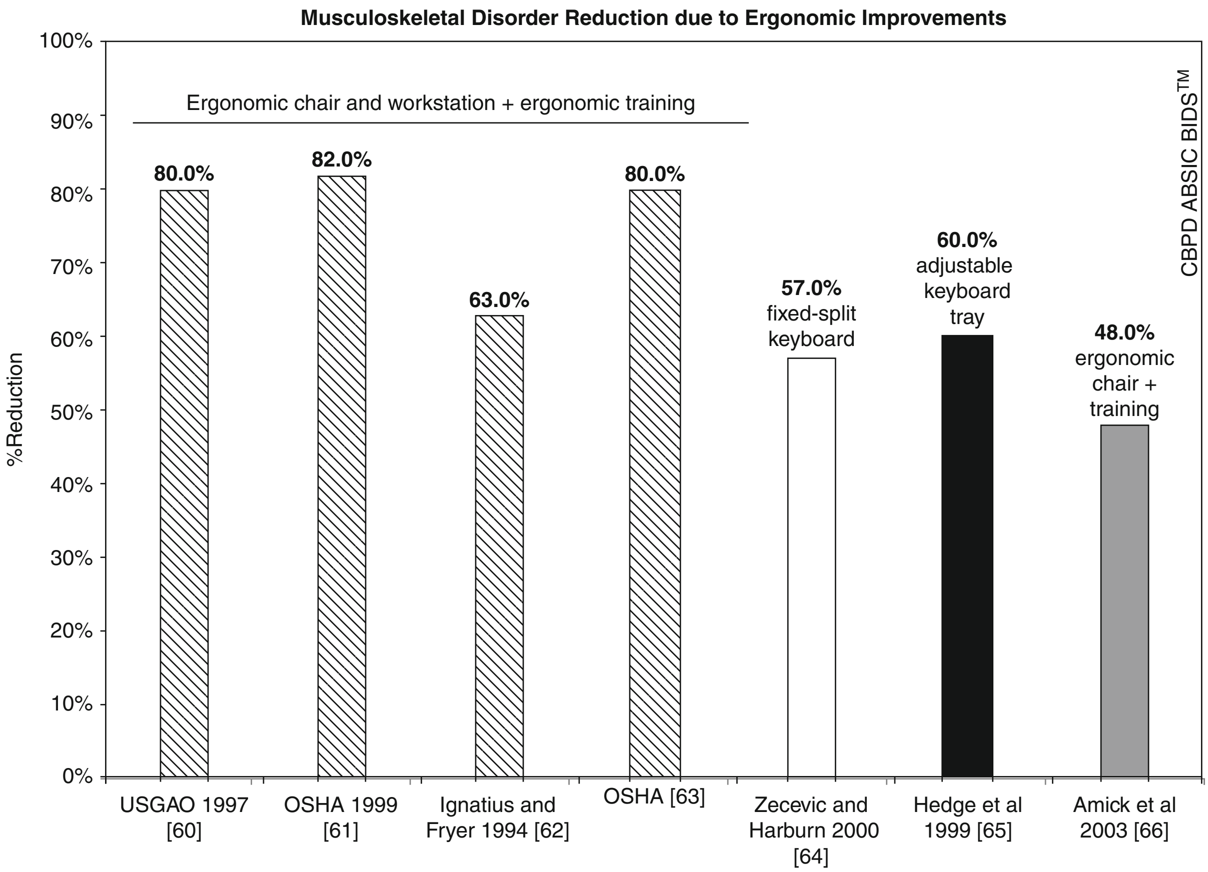
Guidelines for Sustainable Material Selection for Health
Specify materials that do not irritate the skin with contact to avoid dermatological conditions
Specify materials that do not outgas toxins to avoid respiratory/allergy and asthma
Specify materials that do not degenerate into respirable fibers or emit radon to avoid cancers
Specify materials that are not fire hazards causing respiratory illness or death
Specify materials that do not foster mold or mildew leading to respiratory symptoms
Specify materials with low embodied energy and low transportation costs to reduce outdoor air pollution

Guidelines for Sustainable Interior Design and Furnishings for Health
Specify furniture ergonomics to reduce musculoskeletal disorders (MSD)
Design spatial layout/density to reduce transmission of contagious illnesses (flus, colds)
Design spatial layout to reduce falls and tripping
Design layout and specify surfaces to reduce infections transferred by contact with hands-free design
Design spatial layout for enhanced physical activity to reduce obesity and related health concerns

Sustainable Maintenance and Operations and Health

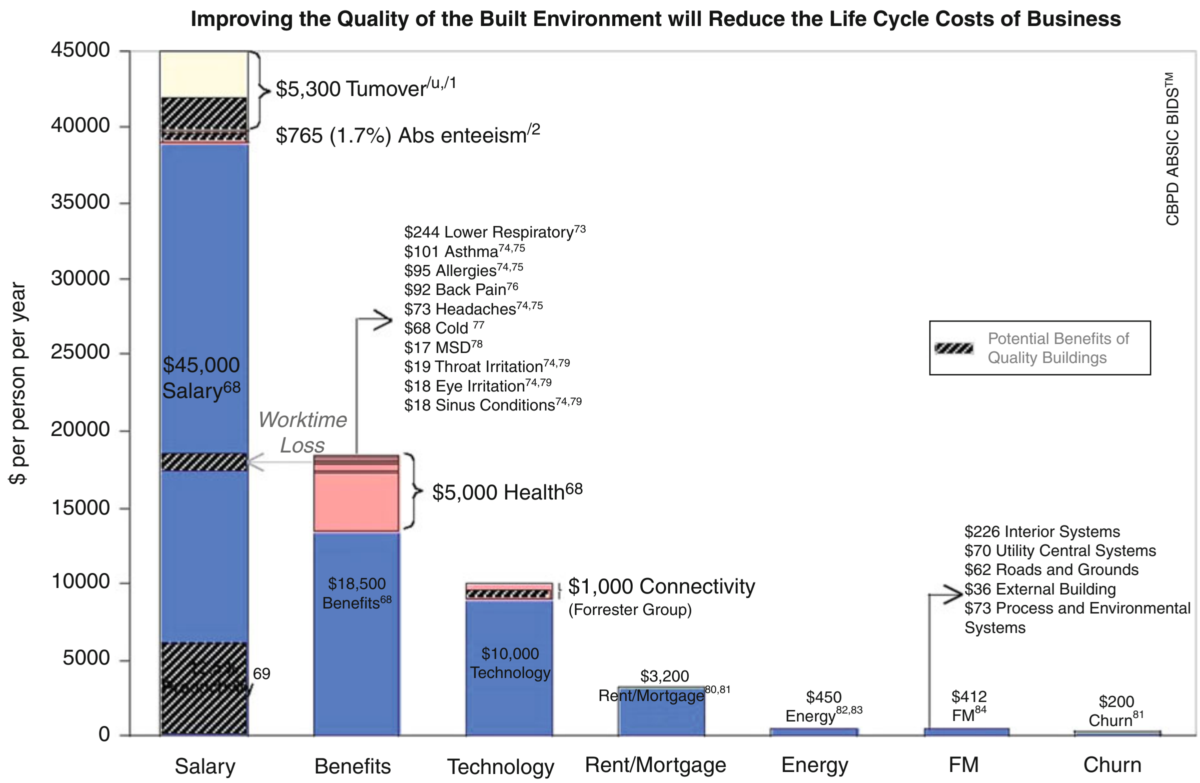
Needless to say, each of these design decisions will become obsolete if there is no commitment to long-term maintenance and operational standards. The building enclosure, HVAC, and lighting systems must be continuously commissioned to maintain the healthy conditions intended. Standing water, dampness, and mold must be prevented. Occupant densities must be managed, and furniture and finishes must continue to meet the health standards set.

In addition, human activities in buildings and the products they bring in must also be selected for health. Cleaning supplies, plants, fertilizers and herbicides, office and teaching supplies must all be environmentally benign. In addition, food and water quality should be monitored for health, including guidelines for vending machines. Waste must be effectively managed since it is a natural breeding ground for roaches, rodents, and other pests, *and* an opportunity for recycling or composting. While this research team has not evaluated the studies that may link poor



Sustainable and Healthy Built Environment. Figure 13

A number of international studies link Musculoskeletal disorder reduction due to ergonomic improvements



Sustainable and Healthy Built Environment. Figure 14
The true cost of business extends well beyond mortgage and energy costs, to include salaries, benefits, technological and spatial churn. Improving the quality of the built environment can be offset by sustained health benefits

maintenance and operation practices to health concerns, it is clear that any degradation in as-built performance will result in health consequences equally serious as those of poor design, engineering, and construction.

Calculating the Life Cycle Benefits of Sustainable Design and Health

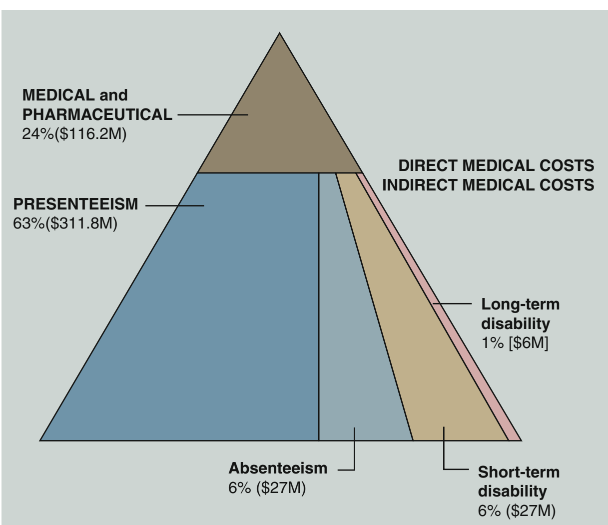
The work of the faculty, researchers, and graduate students of the Center for Building Performance and Diagnostics at Carnegie Mellon and the Advanced Building Systems Integration Consortium extends beyond the pursuit of building case studies that link the quality of buildings to productivity, health, and life cycle sustainability. The development of the BIDS™ tool is based on the identification of economic, environmental, and human life cycle cost benefits related to buildings and communities in order to calculate the return on investment of high-performance building systems (see http://cbpd.arc.cmu.edu/ebids). Figure 14 helps to reveal the diverse building-related costs of doing business in US offices, including salaries and health benefits, technological and spatial churn, rent, energy and maintenance costs. This cost is normalized in dollars per person per year, rather than cost per square foot, since the employee represents both the greatest cost and the greatest asset to an organization.

The CBPD research identified that across independent nonprofit organizations, human resource research firms, and the US government, the average employer cost for health insurance was approximately $5,000 per employee per year in 2003 [8, 14, 17, 66, 70]. Within this $5,000 expense, the CBPD has been able to identify the cost of several specific health conditions and illnesses that can be linked to the quality of the indoor environment, including: colds, headaches, respiratory illnesses, musculoskeletal disorders, back pain (shown in Fig. 14), which account for roughly $750 of the $5,000 annually spent per employee, or 14% of all annual health insurance expenditures.

The direct costs for medical attention and pharmaceuticals would be multiplied further with the indirect costs of reduced speed and accuracy on task, and lost work time due to absenteeism. Beyond the organizational and human costs of worker absenteeism, however, Paul Kemp in Harvard Business Review introduced the term "presenteeism" to reflect the more typical and serious condition of individuals coming to work sick because they cannot afford to miss more work hours or important meetings [30]. While the measured costs of presenteeism are not well documented, there is a modest literature to help quantify the effective work time that is lost on the job due to headaches, colds, flus, and back pain (see Fig. 15, [42]).

The importance of quantifying the financial, environmental, as well as human health and productivity impacts of design decisions is critical to the advancement of sustainable buildings and communities. In his 1998 book *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*, John Elkington [18] introduces the importance of adding social and environmental impacts to economic performance in a triple net present value calculation. To accomplish this, it is critical to quantify the environmental costs of using energy and raw materials without caution, as well as the human health and performance costs of poor land use planning and building design and operation. For the past 10 years, the CMU Center for Building Performance and Diagnostics has been building the economic baselines for triple bottom line calculations for offices, schools, and hospitals (see Fig. 16).

The calculation of life cycle benefits of better design, engineering, and management of hospitals, for example, would include variables such as the average length of stay per illness, at 4.6 days per patient in US hospitals [53]; average cost of hospital stay, set at $1,217 per day in US hospitals [67]; patient reinfection rates, estimated at 2.16/10,000 patient days in US hospitals [51]; average cost of these nosocomial infections, estimated at $27,000 plus 12 day increase in hospital stay [50]; and the average cost of nurse turnover, at $13,800 per nurse per year [2, 37, 38]. The magnitude of these costs would clearly justify significant investment and



Source: Back One

Figures are based on annual data for 2000 workers' compensation accounted for less than 7% of indirect medical costs

Condition	Prevalence	Average productivity loss	Aggregate ammual loss
Migraine	12.0%	4.9%	$434,385
Arthritis	19.7	5.9	865,530
Chronic lower-back pain (without leg rain)	21.3	5.5	858,825
Allergies or sinus trouble	59.8	4.1	1,809,945
Asthma	6.8	5.2	259,740
GERD (acid reflux disease)	15.2	5.2	582,660
Dermatitis or other skin condition	16.1	5.2	610,740
Flu in the past two weeks	17.5	4.7	607,005
Depression	13.9	7.6	786,600

Source: Debra Lerner, William M. Rogers, and Mong Chang, & Tofts-New England Medical Center

Sustainable and Healthy Built Environment. Figure 15
While absenteeism is a cost of business, presenteeism – coming to work with colds, flus, and back pain for example – may have an even greater impact on the *bottom line*

Example Measures of Cost-Benefit Performance for Different Building Types

Offices	Schools	Hospitals
O&M, Energy & Water Worker Health Attraction-Retention Individual productivity Absenteeism/ Presenteeism Organizational productivity Market share Customer speed to market waste cost/ benefits Litigation/ Insurance/ Tax SBS	O & M, Energy & Water Teacher health Student health Teacher turnover Student test scores college placement Absenteeism/ Plasenteeism Drop-out rates No child left behind waste cost/ benefits	O & M, Energy & Water Length of stay/ Recovery rates Nosocomial infections Patient falls Staff health Staff turnover Absenteeism/ Presenteeism Bed vacancies cost/ Bed profit Bed waste cost/ benefits Medication errors

Sustainable and Healthy Built Environment. Figure 16
Measuring "productivity and health" in different building types will require careful identification of critical outcomes and consistent data collection

reinvestment in the quality of hospitals to ensure long-term health and productivity.

Cars and laptops are purchased with far more comprehensive life cycle considerations than buildings, and yet the life span of cars and laptops are often 5 years or less. Since buildings are built for 30, 50, or even hundreds of years, it is imperative that the client and design community begin to address life cycle costs of materials, components, and integrated systems with triple bottom line decision making to ensure the sustainability of economic, environmental, and human health and productivity.

Health and the Built Environment: A Research Mandate

Sustainability is in truth all about health. Energy/material extraction and use and atmospheric, water, and land pollution are as significantly health-related issues as they are environmental conservation issues. Certainly the design and maintenance of building enclosures, HVAC, lighting, and interior systems are directly linked to our short- and long-term health, as the evidence collected in this chapter has begun to prove. Human health in relation to the built environment is one of the most critically needed research efforts, requiring both extensive experimental and field research efforts. Controlled laboratory experiments need to be carried out simultaneously with experiments in the field – to map chains of consequence, and identify possible building-related causes for respiratory, digestive, circadian, musculoskeletal, circulatory, and nervous system illnesses, as well as other health-related concerns. Yet in the USA, at least, there is remarkably little federal investment in defining and valuing healthy buildings and communities.

One cannot overstress the importance of defining key national and international research directions for addressing the impact of the built environment on health. Bringing together emerging knowledge about the importance of land use, building enclosure, HVAC, lighting, and interior design decisions, with the life cycle justifications to ensure their implementation, is critically needed. Sustainable buildings and communities have the potential to deliver the highest quality air, thermal control, light, ergonomics and acoustic quality, as well as regionally appropriate access to the natural environment, which are integral to human health.

In the face of rapid changes in the built environment, the importance of proving that sustainable design and engineering improves health, productivity, and quality of life has never been more important. Indeed, the advances most critically needed for environmental sustainability will constantly be slowed by least first-cost decision making, unless the health-related benefits of sustainable buildings and communities are definitively revealed.

Note

This chapter builds upon the paper "Sustainability and Health are Integral Goals for the Built Environment" by Loftness, Hartkopf, Lam, Snyder et al., published in Healthy Buildings 2006 Lisbon, Portugal June 4–8, 2006.

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Sustainable Built Environment, Introduction

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Article Outline

Defining Sustainability in the Built Environment

Sustainable design is a collective process whereby the built environment achieves unprecedented levels of ecological balance through new and retrofit construction, toward the long-term viability and humanization of architecture. Focusing on environmental context, sustainable design merges the natural, minimum resource conditioning solutions of the past (daylight, solar heat, and natural ventilation) with the innovative technologies of the present, into an integrated "intelligent" system that supports individual control with expert negotiation for resource consciousness. Sustainable design rediscovers the social, environmental, and technical values of pedestrian, mixed-use communities, fully using the existing infrastructures, including "main streets" and small town planning principles, and recapturing indoor-outdoor relationships. Sustainable design avoids the further thinning out of land use, and the dislocated placement of buildings and functions caused by single use zoning. Sustainable design introduces benign, nonpolluting materials and assemblies with lower embodied and operating energy requirements, and higher durability and recyclability. Finally, sustainable design offers architecture of long-term value through "forgiving" and modifiable building systems, through life cycle instead of least-cost investments, and through timeless delight and craftsmanship.

Seven Principles for the Design of a Sustainable Built Environment

A sustainable built environment depends on the following seven principles:

1. An integrative, human-ecological design approach
2. Changing approaches to land use and community fabric
3. The effective use of natural, local, and global resources to reduce infrastructure loading and maximize infrastructure use
4. The design of flexible systems, integrated for comprehensive performance delivery
5. The use of sustainable materials and assemblies
6. The design for life cycle instead of first cost
7. The promotion of infrastructures for water, energy, transportation, and connectivity to sustainable neighborhood amenities

How Does this Broad Definition Translate into an Encyclopedia for Sustainable Built Environments?

While it may not be immediately evident, a sustainable built environment spans dozens of professions, from urban planning to architecture to engineering to interior design to material science to social science and beyond. Sustainability is a revolution for educational pedagogy and content. Moreover, it requires a level of transdisciplinarity that challenges professional roles and creates new collaborative processes. To profile the breadth of science and engineering knowledge that is

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critical to advancing sustainable built environments, multiple encyclopedia sections would be needed, one each for: public policy and economics of a sustainable built environment, architecture, mechanical engineering, lighting engineering, material engineering, water engineering, energy engineering, as well as urban design, landscape and urban infrastructure engineering. By necessity a single section on sustainable built environments must offer a sampling of the science and technology expertise required. This section has gathered 15 leading authors from around the world to provide insight into the breadth of knowledge needed, leaving substantial content for expansion around each of the following critical knowledge bases:

1. The scale of the building sustainability problem and the opportunity
2. Building enclosures for sustainability
3. Building mechanical systems for sustainability
4. Daylighting and lighting for sustainability
5. Interior systems and materials for sustainability
6. Water and the built environment
7. Energy generation and sustainable buildings
8. Landscape sustainability
9. Land use and sustainability
10. Integrated delivery processes for sustainability

The following sections introduce these chapters within the broader knowledge base for substantially advancing our built environment from one that consumes and destroys to one that generates and revitalizes.

The Scale of the Sustainability Problem and the Opportunity

The building sector is the biggest "player" in the energy use equation and can have the greatest impact on maximizing energy supply and minimizing energy demand while providing measurable gains for productivity, health, and the environment. In the USA, commercial and residential buildings use 70% of total US electricity and are responsible for over 35% of total U.S. greenhouse gas emissions [17] (Fig. 1, CBPD).

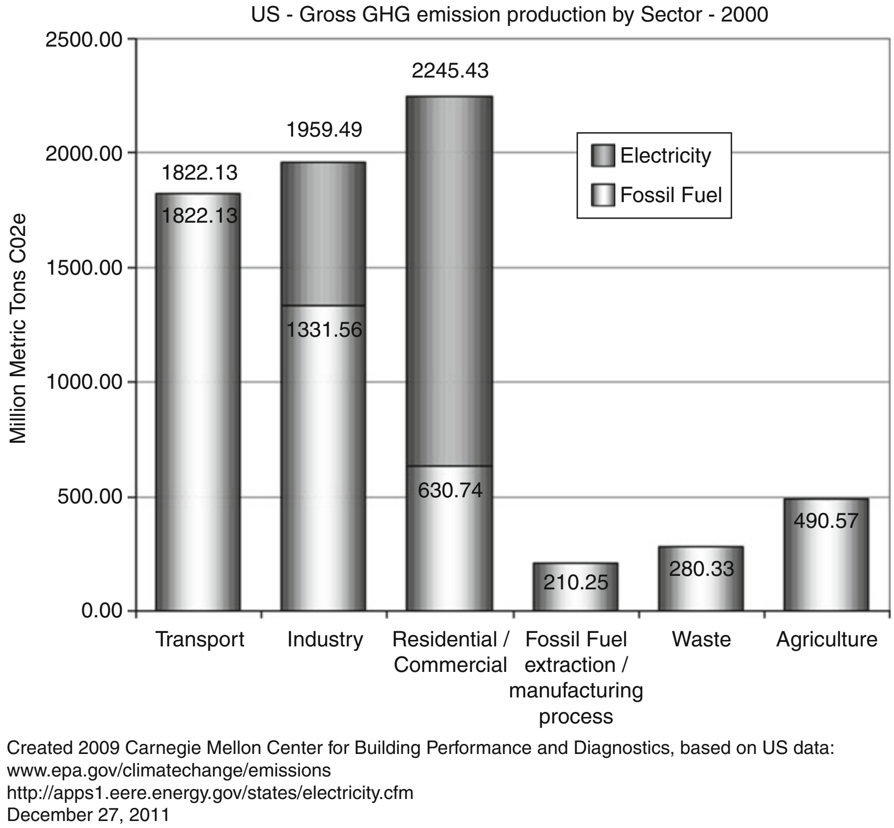
Equally significantly, however, are other environmental statistics related to the built environment: material use, water use, waste production, health, productivity, manufacturing and transportation costs, and climate change. Buildings use 40% of the raw materials globally and 14% of the potable water in the USA. Building activity in the USA also contributes over 136 million tons of construction and demolition waste (2.8 lbs/person/day), and 35% of US greenhouse gas emissions [1].

These statistics underscore the impact of buildings and the built environment on global energy use and climate change, on water and material use. Through land use policies and actions, the built environment generated most of the increases in transportation energy use in the last decade. The impact is even more substantial when human and environmental health, land use and community, as well as indoor environmental quality are factored into sustainability. In short, the scale of the sustainability challenge in the built environment must include:

The role of the built environment on global energy use and climate change
The role of the built environment on health and indoor environmental quality
The role of the built environment on water use
The role of the built environment on material depletion
The role of the built environment on mobility and sustainable infrastructures

Two chapters have been included in this section to begin the dialogue. In the entry entitled "► Sustainable and Healthy Built Environment," Vivian Loftness has introduced a framework for ensuring that building and communities are designed to achieve the highest level of human health outcomes while generating the lowest environmental footprint [25]. Across 30 years of teaching, researching, and even administration as Head of the School of Architecture at Carnegie Mellon, the author has been developing a data base of research linking building components and systems, land use approaches and infrastructures, to health, productivity, and other outcomes of critical importance to decision-makers, captured in this chapter on buildings and health.

In the entry "► Resource Repletion, Role of Buildings," Braungart, Hansen, and Mulhall introduce the massive responsibility of the design community to not only select materials and assemblies for human health and sustainability, but to use environmental life cycle analysis to design for the regeneration of material resources rather than the ongoing depletion. Michael Braungart is the founder of EPEA International Umweltforschung GmbH, and co-founder of McDonough Braungart Design Chemistry (MBDC).



Sustainable Built Environment, Introduction. Figure 1
The building sector is the greatest contributor to climate change, exceeding both industry and transportation

A professor of Process Engineering at the University of Applied Sciences in Suderburg (Fachhochschule Nordostniedersachsen), Dr. Braungart is the co-author of the seminal book *Cradle to Cradle* with William McDonough [2].

These discourses are critical to public policy and to public and private investment. They are also critical to setting the stage for standards, research, and innovation to ensure that the built environment is no longer the cause of depleting resources and reduced health, but a source of sustainable actions for regenerating those resources and for expanding access to a shared quality of life.

Building Enclosures for Sustainability

Entire civilizations have successfully prospered in highly diverse and challenging climates without depleting natural resources beyond the ability of those resources to naturally regenerate. In large part, this success has been achieved through highly responsive, even intelligent building enclosures. Each climate commands a different strategy for natural conditioning, as so eloquently introduced in Don Watson's entry on "► Bioclimatic Design." Emeritus Chair and Professor of Yale University and former Dean of RPI's School of Architecture, Don Watson is a leading sustainability practitioner and author who received the 2008 US Green Building Council Leadership Award, and the American Institute of Architect's Presidential Citation, for his contributions to sustainability in the built environment. Most critically, Don Watson is a preeminent scholar on the subject of Climate and Architecture, and author of standards and textbooks used worldwide, beginning with his McGraw-Hill textbook *Climatic Building Design: Energy Efficient*

Building Principles and Practices [3]. *Buildings and Climate Change* [4], the United Nations Environment Program (UNEP) captures the breadth of these regional design responses and reminds the design community of their continuing importance for sustainability (Fig. 2, www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf).

Dr. Volker Hartkopf and Senior Researcher, Azizan Aziz build on these climatic imperatives and introduce the richness of design responses in their entry on "▶ Facades and Enclosures, Building for Sustainability." Professor of Architecture and Director of the Center for Building Performance and Diagnostics at Carnegie Mellon University, Volker Hartkopf has led an industrial and government consortium dedicated to advanced building systems integration for performance through collaborative research, demonstration, and policy for over 30 years. In collaboration with a faculty team that includes Azizan Aziz, Dr. Hartkopf's leadership led to the construction of the Intelligent Workplace, a living laboratory for innovation in building materials, components, and integrated systems for improving human comfort and health, individual and organizational productivity, and environmental sustainability [5].

To fully explain the enclosure science and the engineering innovation that is critically needed to ensure the highest performance outcomes for each climate and building type, a wide range of chapters would be needed:

Energy conserving enclosures – insulation and airtightness
Energy conserving enclosures – shading
Radiant barriers and roof ventilation
Passive solar heating
Natural and stack ventilation
Time lag cooling
Night sky cooling
Earth tubes and radiant cooling
Evaporative and desiccant cooling
Earth sheltered design

While the ecological functions of green roofs are discussed in the Sustainable Landscape Design section, three critical topics are in this section. Professor Robert Hastings of the EcolePolytechniqueFederale de Lausanne has written the entry "▶ Passive Solar Heating in Built Environment." As managing director of Architecture, Energy & Environment GmbH in Switzerland, Robert Hastings is a leader in the IEA Task 28 – Solar Heating and Cooling. A prolific author with a long list of technical publications on energy efficiency, he co-edited *Solar Energy Houses: Strategies, Technologies and Examples* published by Earthscan [6]. This chapter gives a highly illustrated overview of the breadth of passive solar systems in use throughout Europe and North America, and sets the stage for the next chapter by Kathrin Klingenberg on the *PassivHaus*.

Kathrin Klingenberg is the Co-Founder and Director of the Ecological Construction Laboratory and the Passive House Institute in the USA (PHIUS). A long-term collaborator with the PassivHaus Institute in Europe, she co-authored the book *Homes for a Changing Climate: Passive Houses in the US* [7], to emphasize both the potential of passive house design to dramatically reduce or eliminate thermal conditioning in homes, and the importance of climate-specific approaches to balancing conservation and passive conditioning.

The final entry in this critical area of science and technology for building sustainability is "▶ Natural Ventilation in Built Environment" by Derek Clements-Croome and Tong Yang. Editor of Intelligent Buildings International Journal and Emeritus Professor of the University of Reading, Derek Clements-Croome is the CIB Coordinator for WO98 Intelligent and Responsive Buildings and co-author of the book *Naturally Ventilated Buildings* published by E & F N Spon [8]. Co-authored with Dr. Tong Yang, research associate at Loughborough University, this chapter illustrates the potential for natural ventilation and natural cooling to ensure the highest level of thermal comfort and air quality at the lowest energy cost – through design and engineering innovation.

Building Mechanical Systems for Sustainability

"The best mechanical system is one that you never need to turn on." In a prophetic and visionary statement by one of the leading engineers worldwide, Kevin Hydes PE calls for dramatic changes in the role of the mechanical engineers in practice. Former President of Keen

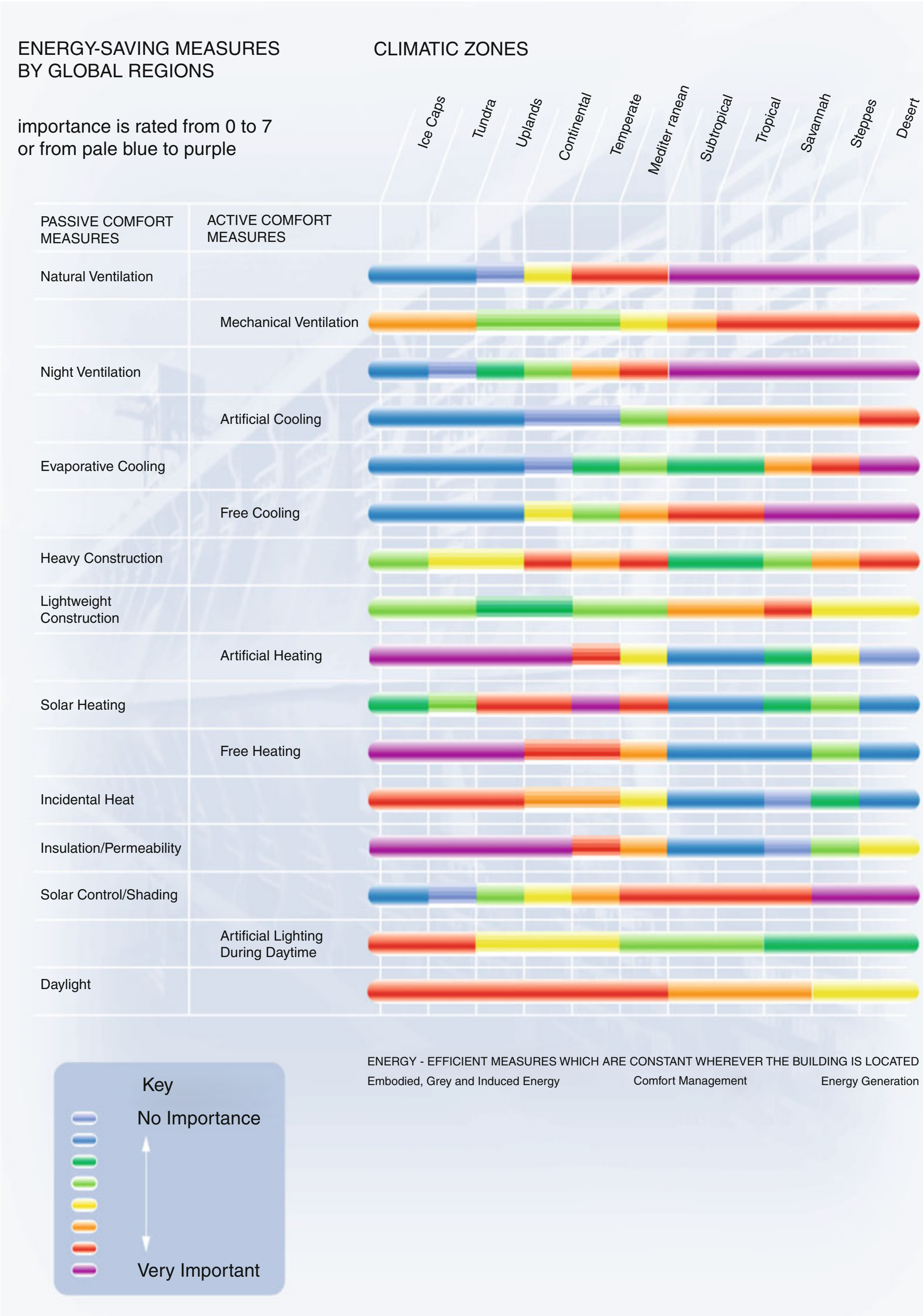


Table. 2.20
Energy saving measures by global regions.
Source: Jones 1998.

Sustainable Built Environment, Introduction. Figure 2
Climate-specific natural conditioning can displace significant energy loads ([4], *Buildings and Climate Change*)

Engineering, later Stantec, Kevin Hydes is today President and CEO of the Integral Group – an interactive global network of design professionals collaborating to achieve deep green engineering. A founder of the Canadian GBC, Past Chair of the Board of Directors of the USGBC and the World Green Building Council, he co-authored the *Ecological Engineer* from Ecotone Publishing [9]. Kevin Hydes introduces the breadth and importance of sustainable mechanical engineering, and the changes in practice that will be critical to a sustainable future, in the entry "▶ Sustainable Heating Ventilation and Air Conditioning." A dedicated section on the science and engineering of building mechanical systems for sustainability could include:

Heating and cooling integrated systems for delivered energy efficiency
Water based thermal conditioning systems
Displacement ventilation and underfloor air systems
Heat recovery, energy recovery and desiccant ventilation
Commissioning for sustainability
Building automation systems and occupant controls for sustainability
Integrated solar power, hot water, heating and cooling systems

Daylighting and Lighting for Sustainability

Over 10% of all US energy is used for lighting buildings, much of this during the daytime when daylight is abundant. Effective daylighting can yield 30–60% reductions in annual lighting energy consumption. If complemented by cutting-edge electric lighting, the residual energy demands for lighting would be less than 10% of today's demand. For this reason, design and engineering for daylighting with integrated electric lighting sustainability would have the most significant impact on energy savings of any investments in the built environment. Dr. John Mardalievic's entry on "▶ Daylight, Indoor Illumination, and Human Behavior" offers an in-depth introduction to daylighting buildings, building the readers understanding of the vocabulary, guidelines and metrics of the well-tempered daylit environment. The chapter further explores daylight modeling, the human impacts of daylight on visual comfort, health and productivity, and ends with an overview of advanced glazing systems and materials. Helmut Koester's entry on "▶ Daylighting Controls, Performance and Global Impacts" addresses the most critical design and engineering innovations needed for ensuring daylight's massive contribution to energy and carbon savings. Architect and inventor of one of the most innovative daylight management technologies, Helmut Koester is the author of *Dynamic Daylighting Architecture: Basics, Systems, Projects* published by Birkhauser Press [10]. This chapter introduces glazing innovations with external and internal layers for effective daylighting and view, as well as shading, glare, and brightness contrast control, with a companion chapter on Daylight, Indoor Illumination and Human Behavior in the Solar Radiation section of the Encyclopedia. Alongside daylight innovations, low-energy high-performance electric lighting advances are also critical for sustainability, suggesting a number of other important topics for future articles:

Lighting and Daylighting for Human Health and Performance
Daylighting controls, performance and global impacts
Electric lighting innovations for sustainability
Electric lighting control innovations for sustainability
Regional design/engineering innovations for balancing view, light, heat, and air

Interior Systems and Materials for Sustainability

While enclosure, mechanical, and lighting systems dominate the energy conservation and carbon footprint discussions, interior systems play a significant role in energy use over time and become a dominant driver for indoor environment quality, material conservation, and human health and productivity outcomes. Innovation is occurring in number of important arenas, with one included in this section:

Interior systems for indoor environmental quality
Interior systems and systems integration for energy conservation
Interior systems for material/resource conservation
Interiors for organizational and individual productivity
Evidence based design for improving IEQ and health
Biophilia

In the entry "▶ Indoor Environmental Quality and Health Improvement, Evidence-Based Design for," Dr. Charlene Bayer provides a critical introduction to the breadth of challenges and opportunities for the design of interior systems for sustainability. As Leader of the Environmental Exposures and Analysis Group at the Georgia Tech Research Institute (GTRI) and Director of Georgia Institute of Technology's Indoor Environment Research Program, Dr. Bayer brings over 30 years of experience to the discussion of indoor environmental quality. She introduces the power of a field research–based approach to facilities design "that treats the building and its occupants as a system and gives importance to design features that impact health, well-being, mood and stress, safety, operational efficiency, and economics." Evidence Based Design (EBD) is one of the most important recent contributions to ensuring sustainable built environments – shifting the focus from designed performance to the installed performance of integrated building systems, and re-centering goals to focus on the productivity and health of individuals and organizations.

Energy Generation and Sustainable Buildings

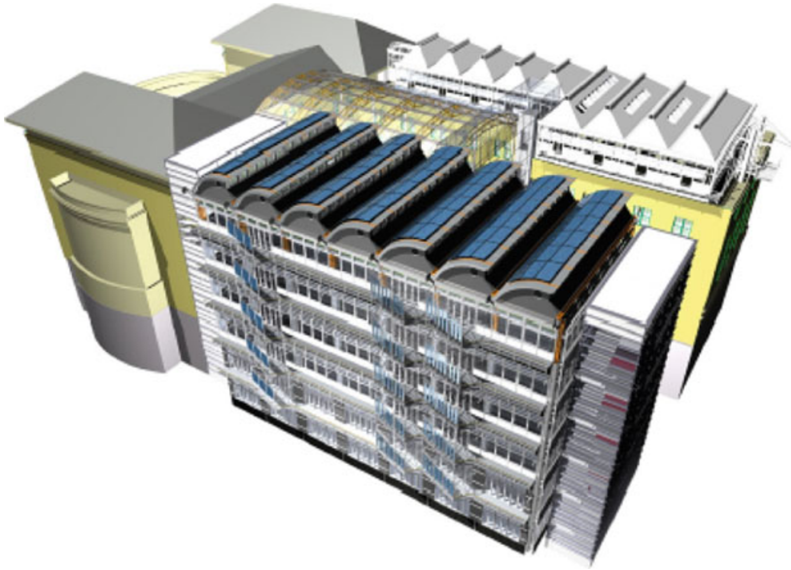
In 2002 [11], architect Edward Mazria issued the 2030 challenge, asking the global architecture and building community to adopt 60% energy savings goals by 2010, 70% by 2015, advancing each 5 years by 10% to achieve carbon neutrality by 2030 for all new buildings and major renovations (http://www.architecture2030.org/). The 2030 challenge demonstrated that these targets can be accomplished by "implementing innovative sustainable design strategies, generating on-site renewable power, and purchasing renewable energy (up to a 20% maximum)." While green house gases do not define the entire story of sustainable built environments, they present the largest challenge for designers today because of the multiplied impacts of declining resource availability, increasing outdoor air and water pollution, as well as global warming with all of its serious ramifications for survivability. Demand reduction is the critical first step, with huge potential for dramatic reduction. Sustainable alternatives to energy supply, fully integrated with community and building design, is the critical next step. Alternative energy supply choices and their ramification for building design, engineering and land use planning are introduced in this and other sections of the Encyclopedia:

Managing electricity – plug and process loads, parasitic loads
Combined heat and power (CHP) & building integrated CHP
Site and building integrated PV
Site and building integrated solar thermal
Geothermal, aquathermal, ground coupled HVAC
Bio-fuels and sustainable buildings

This section includes two chapters on thermal and power energy systems with major implications for the building industry. The authors have the most cutting-edge knowledge of the breadth and depth of the engineering challenges and opportunities because they have recent dissertations on the topics. Nina Baird, an expert on open and closed loop aqua-thermal district energy systems, gives a rigorous overview of the breadth of ground coupled heating and cooling systems that can serve individual buildings, campuses, or entire communities, in the entry "▶ Geothermal Conditioning: Critical Sources for Sustainability." Fred Betz, senior sustainable engineer at Affiliated Engineers, gives a rigorous overview of innovations in renewable fuels for power and heat generation in the chapter *Bio-fuels and Sustainable Buildings.*

Combined heat and power, photovoltaics, and solar thermal have been included in the other sections of this encyclopedia. In pursuing these innovative energy sources, it is critical for the design community to aggressively pursue both "exergy" and energy cascades. In their PLEA 2004 [12] paper, "Critical analysis of exergy efficiency definitions applicable to buildings and building services," Boelman and Sakulpipatsin discuss the importance of matching each type of energy (electricity, low and high temperature thermal), and their energy potential, to their thermodynamically optimal uses in buildings and building services. Exergy begs the question 'if the Earth provides moderate temperature cooling and the Sun provides moderate temperature heating, can we design thermal conditioning systems that use these sources directly with maximum effect, leaving electricity for more challenging tasks?'

At the same time, a sustainable built environment would use the building as a critical element in energy



Sustainable Built Environment, Introduction. Figure 3
Carnegie Mellon's vision for a "Building as Power Plant" uses energy cascades to meet power, cooling, heating, and hot water demands, matching loads to optimize the 'exergy' of each source, with excess energy for export to the campus grid

cascades, using the "waste" heat from one process for the next, and using the building mass as a "battery" for thermal energy. In conceiving the "Building as Power Plant," Volker Hartkopf suggests that each new building should be a net energy exporter: first combining energy efficiency with passive conditioning in an "ascending" strategy of daylighting, natural ventilation, passive cooling, and passive solar heating; then integrating "cascading" energy uses, with the waste heat from power generation cascading to cooling energy, waste heat from cooling cascading to heating energy, and waste heat from heating cascading to hot water through the integrated design of the building, including the management of peak loads and time shifts for each energy source [13] (Fig. 3).

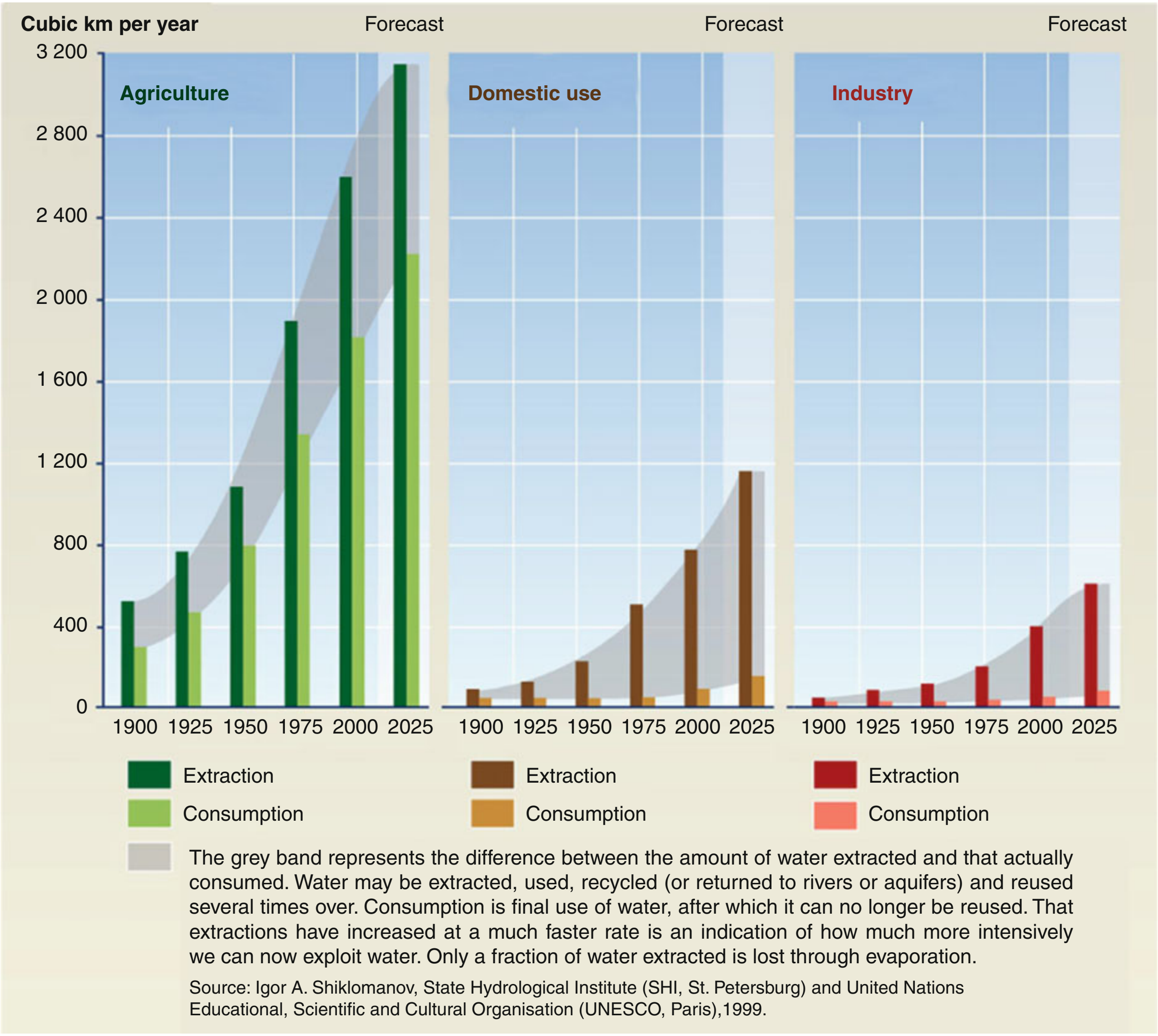
Water and the Built Environment

While energy is the central focus of most sustainability chapters, due to the rapid depletion of nonrenewable sources and the serious global warming and green house gases produced, water is an equally serious challenge. Global demands for freshwater are depleting freshwater availability at a rate that is alarming. While 70% of global freshwater demand is for agriculture, the 20% freshwater used in the building sector is growing at a rapid rate – with the highest level of inefficiency. As with energy, the greatest opportunities for conservation at the lowest first cost and the highest payback reside in the building sector. UNEP illustrates this with charts that differentiate extraction and consumption per end use sector (see Fig. 4), highlighting the major opportunities for the building sector to dramatically reduce its extraction demands through efficiency, gray water, and black water innovations [14].

Sustainable Built Environments include a range of innovations for water conservation and cascading water use, including:

Water conservation in buildings
Rainwater capture and use
Grey water systems
Black water systems
Closing the loop – regenerative fresh water systems

The concept of "cascading" water use parallels the concept of exergy – ensuring the use of potable or freshwater for its highest and best use, then using the gray "waste" water for its highest and best use, and finally the reuse of black water through innovations in sustainable filtration, with the intention of designing closed loop systems for returning freshwater to the



Sustainable Built Environment, Introduction. Figure 4
While agriculture represents the largest consumer of freshwater worldwide, the greatest waste in freshwater use is the built environment, shown in the difference between extraction and consumption

aquifer. In addition, a sustainable built environment must ensure that deluge and drought, hurricanes and floods do not devastate buildings and communities, or the infrastructures that ensure habitability.

Landscape Sustainability

Explored in the section on Sustainable Landscape Design, the design of landscapes for sustainable sites, neighborhoods, and entire regions has the potential to address a broad range of environmental challenges: water shortages, flooding, brownfields, carbon sequestration, habitats, edible landscapes, and even human health. Through collaborative design, the building community should fully engage the science and technology of:

Watershed planning
Landscape design for brownfields
Landscape design to reduce climate change
Landscape design for net zero water and aquifer recharge

Landscape design for shrinking land
Building and landscape design for biotopes and habitats
Landscape design and quality of life
Cool roofs and cool communities

Many of the tools described in the final chapters of this section embrace the importance of water and landscape sustainability. Ray Cole's entry on "► Rating Systems for Sustainability" highlights how sustainable sites and water are as important as energy, materials, and indoor environmental quality to the sustainable design community. Bill Reed's entry on "► Regenerative Development and Design" erases the lines completely between energy, materials, water, land, and the assurance of a sustainable quality of life.

Land Use and Sustainability

At this point, an encyclopedia on Sustainable Built Environments would move outside the boundaries of the building or even the campus to embrace the growing challenges of land use. There are two divergent challenges that this section would address: rapid urbanization in the developing world and ongoing sprawl in industrialized nations. Both of these rapid changes in land use generate massive and long-term consequences for: energy, water, material resources, infrastructures, abandonment, transportation, agriculture, industry, and a sustainable, shared quality of life. Further explored in the encyclopedia section on Environmental Geology and on Mass Transit, land use practices for sustainability include:

Sustainable urbanism
Urban growth boundaries and transit-oriented development
Town planning for sustainability
Regional planning for sustainability
Coastal planning for sustainability
Civil infrastructures for sustainability
Future sustainable cities
Ecological footprints

All sustainable building designers today reach a point where they realize that even net zero energy and net zero water buildings can be overwhelmed by environmental demands of poor siting, community design, and infrastructures. In the USA, there is an emerging effort to ensure that sustainability includes a number of the most egregious environmental demands. The Center for Neighborhood Technology, for example, is developing a Transit Energy Index (TEI) for buildings, in an effort to ensure that the distance traveled, the type of vehicles and the environmental consequences of that travel are included in the sustainability assessment (http://www.cnt.org). The 2007 book *Sustainable Urbanism: Urban Design with Nature* by Douglas Farr provides a comprehensive introduction to the integration of density and mix, land use and transportation, design for universal accessibility, for human health and for a long-term partnership with nature [15].

Integrated Delivery Processes for Sustainability

The final four chapters in this section define the cutting-edge processes that ensure integrated design and engineering innovation for sustainability. Raymond Cole, Professor at the University of British Columbia and Head of the Environmental Research Group (ERG), provides a worldwide overview of "► Rating Systems for Sustainability." One of the leading experts on sustainable building practices, Dr. Cole has helped to forge the evolution in standards to ensure broad environmental responsibilities for designers – from energy to water to materials to indoor environmental quality to land use – a breadth that has been critical to defining sustainability science and technology for the built environment.

Dr. Khee Poh Lam, Professor of Architecture at Carnegie Mellon University and former Dean at the National University of Singapore, has written the critical entry on "► Sustainability Performance Simulation Tools for Building Design." His leadership in the development and application of energy, lighting, and computational fluid dynamics tools, as well as his development of design compliance tools for sustainable practices, contributes to this expert overview of computational tools and their contributions to ensuring measured environmental outcomes. Laura Lesniewski, a principal in the leading sustainability firm of BNIM, has written the entry on "► Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling." An architect with a significant portfolio of LEED, net-zero and Living Building projects, Laura brings critical insight to the changes needed in professional practice for sustainability, and the changes that range from early multidisciplinary collaboration to the most advanced Building Information Modeling, to embrace the science and technology of sustainability.

A comprehensive description of integrated building delivery processes for Sustainable Built Environments should also include:

Post occupancy evaluation (POE) for quantitative and qualitative feedback
Sustainable specifications and life cycle assessment (LCA)
Cradle to cradle™ design

While textbooks are sorely lacking in POE or LCA for the sustainable design community, the manifesto *Cradle to Cradle*™ by William McDonough and Michael Braungart is unquestionably one of the most critical references for our time [2].

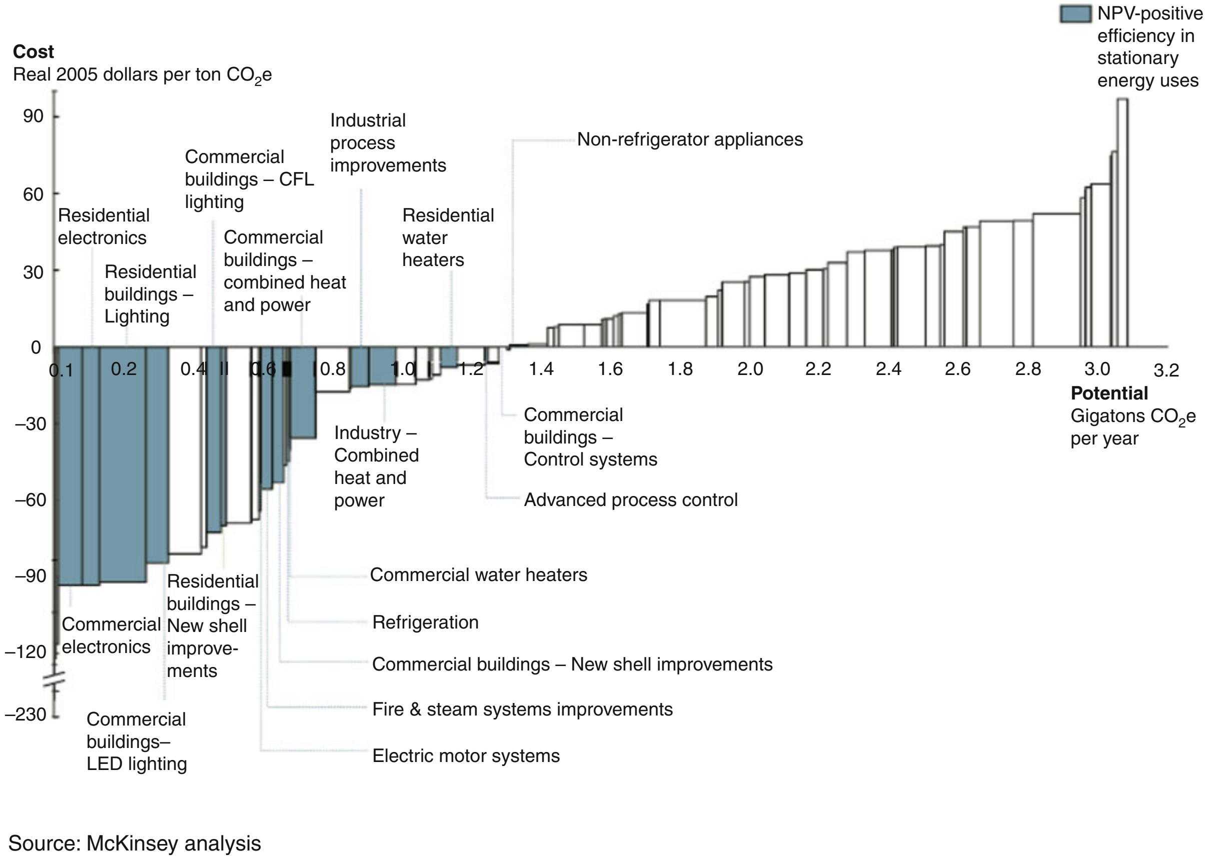
Equally important is the emerging understanding of living buildings, restorative buildings, and regenerative buildings. The deep green efforts of the Living Future Institute to create a visionary path to a restorative future through the Living Building Challenge are critical aspirations for transformational changes in sustainability (https://ilbi.org/lbc). Bill Reed takes these goals and the integrated design processes critical to their success, even further in the final entry of this section – "► Regenerative Development and Design." A principal in three firms, the Integrative Design Collaborative, Regenesis, Inc., and Delving Deeper, Bill Reed was a founding board member of the USGBC and co-author with the Seven Group of *The Integrative Design Guide to Green Building* published in 2009 [16] by John Wiley. In collaboration with Pamela Mang, Bill Reed has written the culminating chapter for this section, creating a framework for an integrative, whole-systems design process to ensure that "projects and processes achieve the highest level of performance across every sustainability metric – and beyond, into regenerating the health of our ecological systems."

Conclusion for Sustainable Built Environments: Policy Matters: the Market Will not Take Care of It

Energy is cheap, especially if the externalities of climate change, pollution, or health are not considered. In the USA, governments, building owners, and consumers do not see energy as a large enough component of their disposable income to even evaluate the return on investing in energy efficiency, much less water efficiency or other sustainability goals. Deregulation has reduced the efforts of major utilities to pursue demand side management and weatherization. At the same time, power unreliability has led residential and commercial building owners to purchase inefficient and polluting standby power rather than consider the significant opportunity to invest in energy efficiency and renewable energy sources. Policy is critical because the market will not act quickly or forcefully. The contributions of buildings to the discharge of four primary pollutants – NO_X, SO_X, CO_2, and particulates – should be fully recognized in the cost of energy, to catalyze owners and occupants to pursue more environmentally responsible buildings and building use patterns.

Federal and state energy efficiency standards, as well as tax incentives, are critical to finally balancing investment between energy supply and demand. Given the major energy excesses in the built environment, reducing demand must be seen as a major energy *source*. The McKinsey report "Unlocking Energy Efficiency in the US Economy" was a revelation for the energy world, finding that carbon reductions through building energy efficiency are the lowest cost per ton with the highest return on investment of any GHG action (Fig. 5, [18]). Investments in "mining" this new energy supply will yield greater economic benefit for a broader array of industries; provide significant gains in reducing environmental pollution; and ensure a longevity to energy "supply" that few other sources can ensure.

Even though the return on investment for energy efficiency dramatically exceeds that of creating new sources, the US dollars in energy supply research and development (R&D) are six times the R&D dollars for reducing energy demand [19]. Yet the modest national investments by the US DOE (of around $3 million per program) in R&D for energy-efficient ballasts, low-E windows, and refrigerator standards reaped national benefits of $9,000, $7,000, and $23,000 per dollar invested [20]. In addition to the obvious benefits of reduced energy demand, dramatically accelerated national investments and policies focused on building energy efficiency will contribute to the following:

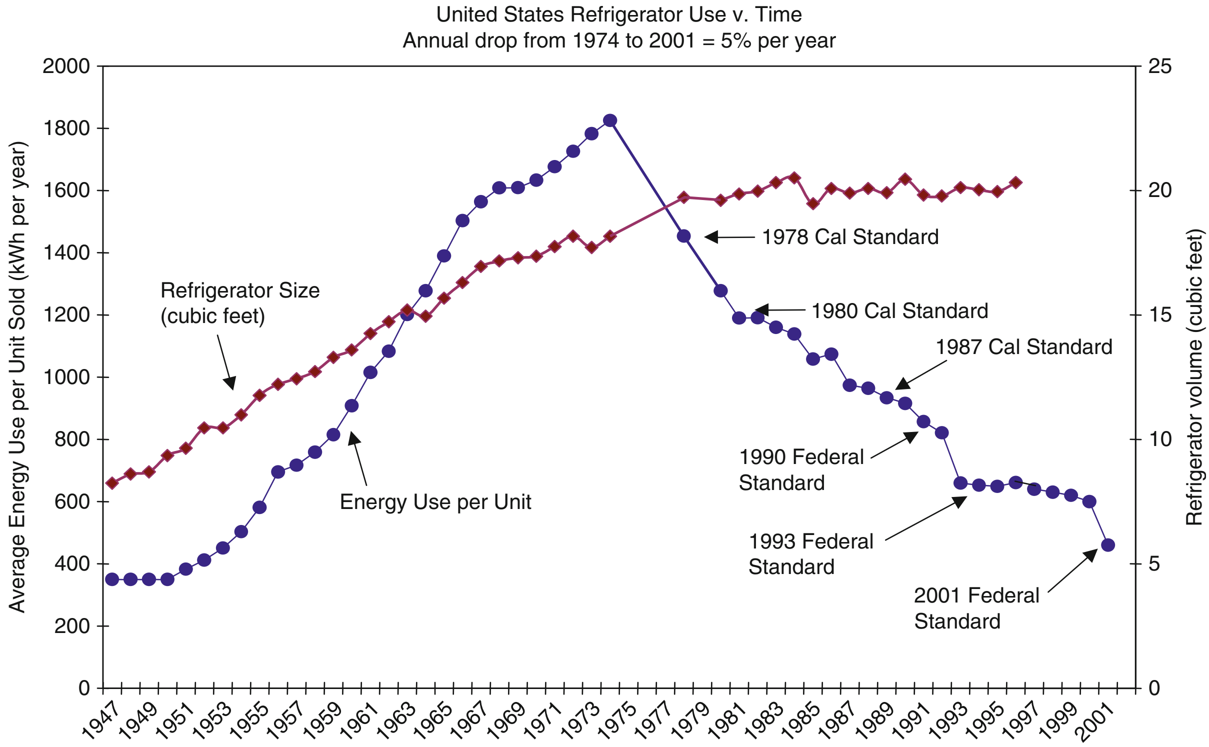


Sustainable Built Environment, Introduction. Figure 5
Carbon reductions through building energy efficiency are the lowest cost per ton with the highest return on investment (http://www.mckinsey.com)

Reduced unnecessary annual energy consumption
Reduced emissions and climate change impacts
Increased peak power capacitance and reliability (energy security)
Improved health, human safety, and security
Improved productivity
Improved quality of life
Increased exports of products and services
Setting a proven example for emerging nations with growing demands

This last point is especially important – setting a proven example in mitigating climate change for emerging economies that will depend on expanding energy resources. Greg Kats argues in a study of the costs and financial benefits of green buildings, "The vast majority of the world's climate change scientists have concluded that anthropogenic emissions – principally from burning fossil fuels – are the root cause of global warming. The USA is responsible for about 22% of global greenhouse gas emissions. Of this 22%, the US building sector is responsible for about 35% of US CO_2 emissions, the dominant global warming gas" [21]. The critical actions needed include massively improving building energy efficiency, building land use, and infrastructure efficiency – in the very near term. This can only be achieved by immediate changes in policy, investment, and research at the national, regional, and industrial level.

Energy efficiency in buildings represents a major untapped resource for energy supply. The development



Sustainable Built Environment, Introduction. Figure 6
Driven by California, national standards led to significant reductions in energy use from key buildings technologies – a major "source" of new energy for the USA

of national standards and the removal of market barriers can lead to significant reductions in energy use from key buildings technologies through their natural replacement cycle ([22], Fig. 6). A 1997 study undertaken by all five national laboratories determined that building energy efficiency could achieve 230MTC of the 400MTC savings needed by 2010 to meet US targets under the Kyoto Protocol [23]. With the addition of innovative combined cooling, heat and power technologies, a further 170MTC could be achieved, fully meeting 2010 goals through the building sector alone. Over the longer term, expanded building R&D budgets, industry- and university-based research, and continuing national policies that focus on building energy efficiency could trigger dramatic improvements in energy and environmental quality in the built environment. Moreover, these investments would ensure ancillary benefits including the revitalization of existing buildings and infrastructures, measurable gains in health and productivity, and a positive influence on energy-efficient growth in the built environment of developing nations.

Investing in building energy efficiency as a new energy "supply" would dramatically surpass production from new oil supplies and power plant investments, as well as offer sustained "sources" of energy that do not generate greenhouse gases. Yet the combined budgets for building research across US government agencies is less than 2% of federally funded R&D, in no way commensurate with the importance of the built environment to our economy and quality of life [24]. Given this paucity of research support, there are only a handful of university Ph.D. programs in the USA focused on energy efficiency and environmental quality in the built environment, an inadequacy that leaves the US industry lagging in its ability to innovate for building energy efficiency.

Given that buildings in the USA account for 70% of electricity consumption, 40% of energy use, 38% of all carbon dioxide (CO_2) emissions, 40% of raw materials use, 30% of waste output (136 million tons annually), and 14% of potable water consumption, and are significantly linked to health and competitiveness, it is critical for the USA to invest in policy, research, and innovation toward more sustainable built environments.

At the same time, all nations need to enact collaborative efforts to ensure that decision-making in the built environment contributes to a shared future of sustainable energy, air, water, land, and material resources, while ensuring a sustainable quality of life for all nations.

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Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling

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Article Outline

Glossary

BIM model A three-dimensional digital simulation, typically of a building or other built form, which is both parametric and database driven.

Building information modeling (BIM) The methodology or process of creating a parametric database-driven digital model of a building or built environment. Understood within the practice of building information modeling, especially on large complex projects, is the collaboration required of various team members during all design and construction phases to add, delete, modify, enhance, or otherwise update the BIM model for the benefit of the overall project and team.

Integrated project delivery (IPD) A project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction [1].

Lean thinking A way to do more and more with less and less – less human effort, less equipment, less time, and less space – while coming closer and closer to providing customers with exactly what they want (value) [2].

Sustainable design An approach to design whereby the needs of the present are met without compromising the ability of future generations to meet their own needs [3].

Definition of the Subject

While a nascent understanding of the need for a more sustainable approach to design and construction has been around for decades, only recently have there been appropriate methods and tools available that are substantial and mature enough to help move a design and construction team toward a more integrated approach and, therefore, a more sustainable project. For these last few decades, progress toward sustainable thinking in both academia and practice has occurred in fits and starts, relying on old tools and methods while attempting to accomplish fundamentally different (i.e., truly sustainable) results. The mainstream availability of integrated delivery processes as well as building information modeling tools that have been tested in the field with positive results suggest that the industry has turned a corner on an integration that matters.

Introduction: Sustainability Through Reintegration

Since Descartes and Bacon, western civilization has clung to two critical notions: humanity's dominance over nature as a God-given right and specialization as the means to dissect nature in order to understand it. Since then the slow evolution of deconstructing the natural world leaves the current generation in a severe state of naiveté, particularly as it struggles to understand the global impact of humanity's collective and cumulative decisions and actions. This gradual loss of wisdom of the interconnected whole leaves today's societies puzzled and overwhelmed in trying to understand what sustainability really means, as

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specialized behaviors, methodologies, and policies have been developed over the centuries. This disintegrated approach, which has been codified and held dear within the design and construction industry, directly reflects a Baconesque tendency toward separation.

As the effects of design and building decisions have become more measurable through quantitative metrics for sustainability, and the impact of these decisions is made more evident, architects and engineers are radically rethinking their approach to design. In addition to engaging numerous disciplines early in the design process, new methods for collaboration have been developed to reduce the traditional redundancy and suboptimization of project goals. Transformational methodologies and tools, particularly integrated delivery processes and building information modeling, are finally dovetailing with comprehensive sustainability goals in buildings and communities.

Sustainable Design and Construction

Indigenous Architecture

In an abbreviated history of sustainable design, McLennan [4] refers to four "beginnings": the Biological Beginning, the Indigenous Vernacular Beginning, the Industrial Beginning, and the Modern Beginning. A brief overview of the last three is noted here, while the biological beginning is addressed under section Future Directions.

A quick survey of the architecture of indigenous cultures reveals a profound understanding of sustainability borne from the realities of their environments. Without the ability to transport materials over great distances, and without the benefit of technological advances such as electricity, combustion engines, and elevators, for example – indigenous populations founded their architecture firmly within the limits of their culture, climate, and place. The use of the term "limits" here is not to be considered pejorative, but rather as a foundational principle of sustainability. Benyus [5] refers to "tapping the power of limits" as a mature understanding of one's place within a whole, as contrasted to the more domineering mentality of a culture that seeks to find boundaries in order to overcome them, as described by Descartes.

The beauty of the Anasazi rock dwellings in Colorado and Utah lies not just in their formal qualities, but in their direct and readily apparent response to their climate and place. An experiential understanding of their climate informs a number of design decisions: orientation, mass, overhangs, the use of local materials, and seasonal variations for protection from hot and cold temperatures, sun, wind, and rain.

Similarly, the nomadic tribes of the North American plains developed portable tipis to support their nomadic culture, made from wood and animal skins readily available in their place, designed to take advantage of prevailing winds for natural ventilation and to protect from sun and wind as needed (Fig. 1).

The igloos of the Inuit in northern climates suggest a multifaceted and deep understanding of snow and ice as a building material. In its stacked form, it provides

Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 1
Indigenous architecture. The tipis of the Crow Nation are built for their portability, with materials readily available. The form and construction of the tipi also encourage natural ventilation

protection from winds and introduces a thermal insulation critical in their climate. The rounded form is appropriate to deflect strong winds and for structural stability with a building block that is not otherwise mechanically secured or tied in place.

Though these, indigenous structures are familiar to many in the western world, each one reveals a profound understanding of sustainability in design and construction that is overlooked today, and all come from a deep understanding of climate, culture, and place. When seen only as rudimentary or sentimental structures irrelevant to current lifestyles, an opportunity for deep learning from multigenerational cultures is missed. The ability to respond intelligently to climate, culture, and place emerges from the time spent in that place, measured in generations rather than years. A generational understanding of place allows sustainable design or building activity to become intuitive. Shy of that, a project team that is not from the place is relegated to an extensive research effort, which at best becomes knowledge, but may not ensure intuitive wisdom.

On the one hand, generational knowledge of place is critical to informing sustainable design. On the other hand, designing for durability can be equally important to sustainability. As societies expanded, larger structures were designed and built to reflect religious, cultural, or political institutions. These structures similarly reflected the climate, culture, and place and were built to last far beyond the generation that built them. In many instances, the generation of builders that began the construction of such buildings, for example the Duomo in Florence, knew that they would not even see the completion of the structure in their lifetime [6]. As defined by the Brundtland Commission, sustainable development is development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7]. The concept of time in terms of generations rather than years is fundamental to understanding true sustainably. As will be explored later in this chapter, the use of integrated project delivery and BIM cannot makeup entirely for the loss of intuitive wisdom born from multigenerational familiarity with place, nor for the cultural shift away from long-term (durable) structures and toward short-term paybacks. These tools do, however, have potential to reconnect that which is lost by way of access to pertinent data (in lieu of experiential learning) and collective wisdom of a diverse and integrated team.

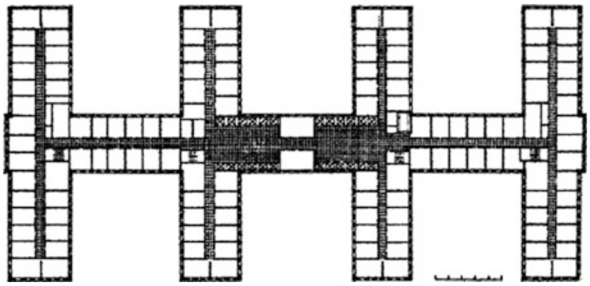
Unsustainable Design and Construction

In the late eighteenth century, the transition from custom-made to machine-made goods as part of the Industrial Revolution impacted the design and construction industry profoundly. Mass production gradually became the norm, suggesting a shift toward interchangeable building parts and materials that were no longer customized for each project. With primary goals of conserving human labor and increasing production, the slow evolution away from culture-, climate-, and place-based structures began. Concurrent with this transformation in the delivery of buildings was a prevailing attitude that natural resources were abundant, even unlimited, and relatively inexpensive to extract. The shift away from generational thinking also began, both in terms of wisdom of the place, as well as building for generations.

While the technological shift in building production was underway, the architecture of the early 1900s preserved a number of place-based principles for daylighting, natural ventilation, thermal mass for cooling, and mixed-use pedestrian lifestyles. As building technology developed, however – introducing automobiles, air conditioners, high-rise elevators, and others – the remaining sustainable principles were lost. With the increased use of manufactured materials, as well as a willingness to transport materials over great distances, projects relied less and less on materials harvested in close proximity to the site (Fig. 2).

With the rise in access to and use of electric lighting, it was possible to design buildings without access to daylight in each space. With air-conditioning, deep floor areas, and windowless spaces, unshaded and sealed building envelopes could provide thermal comfort regardless of climate and place. Each of these innovations gradually and significantly contributed to more energy-intensive buildings and an ever-increasing separation of humans and nature.

Over time, heating, cooling, and lighting were predominantly handled with mechanical systems, rather than taking advantage of climate for natural conditioning. Building codes gradually required uniform



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 2
Narrow footprints. The plan for Detroit's General Motors headquarters, built in 1921, places each worker within 20 ft of an operable window and provides access to views and daylight for almost every room in the building (Architect: Albert Kahn, Inc.)

comfort standards to be maintained, leading the design industry to rely even more on mechanical (and not natural) solutions. Eventually, manufacturers of building products limited their warranties to these tightly controlled conditions, providing even less incentive for the building owner to allow the building to be "open" to the opportunities of natural conditioning and direct contact with place, season, and even time of day. By the mid-twentieth century, the independence of building design and construction from culture, climate, and place had been achieved. A mid-rise building design for Anchorage, Alaska, was indistinguishable from a similar structure in Phoenix, Arizona. No specific reference to place was integrated other than by way of name or superficial decoration.

Eventually, through case studies demonstrating the human health implications of the design of such spaces, a renewed understanding of both the interconnectedness of natural systems to themselves as well as the inherent affiliation between humans and natural systems has emerged. As Kellert suggests in *Biophilic Design* [8]:

- Most of our emotional, problem-solving, critical-thinking, and constructive abilities continue to reflect skills and aptitudes learned in close association with natural systems and processes that remain critical in human health, maturation, and productivity. The assumption that human progress and civilization is measured by our separation from if not transcendence of nature is an erroneous and dangerous illusion. People's physical and mental well-being remains highly contingent on contact with the natural environment, which is a necessity rather than a luxury for achieving lives of fitness and satisfaction even in our modern urban society.

It is a similar renewed understanding of the power of integration that has influenced the explosion in the late twentieth and early twenty-first centuries of new integrated tools and processes, such as BIM and integrated project delivery. As we will see, this relatively recent and renewed understanding of the need for deep integration, including the way in which designers design and builders build, is critical to achieving regenerative design, which will create the foundation for true sustainability in our built environments.

The Modern Sustainable Design Movement

Many consider Rachel Carson's *Silent Spring* [9] of 1962 to be the catalyst of the modern environmental movement and a precursor to the modern sustainable design movement. In her position as a marine biologist with the US Fish and Wildlife Service, she was overwhelmed by the detrimental impacts of the cumulative actions of humans on the environment. In "A Fable for Tomorrow," Carson illustrates the interconnectivity of ecological diversity and the health of humans.

Carson was a catalyst for a new era of environmental thinkers within the EPA, yet the building professions lagged until the energy crisis of the 1970s, when a group of architects, including Sim Van der Ryn and others, focused their efforts on building designs that minimized reliance on oil and maximized reliance on solar energy. In the 1980s, the seeds were being sown to significantly expand the environmental movement beyond the issues of energy conservation. Leaders including BNIM Architects and William McDonough Architects broadened the dialog to include design for material and water resources, indoor air quality, and livable communities. In 1993, the US Green Building Council (USGBC) launched the Leadership in Energy and Environmental Design (LEED) Green Building

Rating System, transforming US attitudes and behaviors toward sustainable design and construction.

The LEED tools, and those emerging in other countries such as BREEAM and CASBEE, were developed for a variety of reasons: to define standards for measuring sustainability; to compare buildings evenly; to transform the construction industry; to raise consumer and client awareness; to stimulate competition; to establish a recognized name for sustainable design; and to educate and integrate the building industry, building owners, and design practitioners. Most significantly for the discussion of integrated design practice, the LEED credit system seeks to promote integrated design; encourage innovative design solutions; improve the life-cycle economics of the project; provide a healthy, productive, and safe workplace for employees; reduce resource consumption; and reduce the negative impact on the environment. These methodologies place real attention on the performance of buildings and communities and their impact on the environment. However, they tend to focus on reducing environmental impact rather than the more challenging goals of rebalancing the relationship between humans and nature, closing the ecological cycles, and restoring or regenerating the earth. A number of far-reaching approaches are challenging the professions even further: Architecture 2030, Living Building Challenge, Cradle to Cradle, REGEN, and One Planet Communities. A key tenet of these approaches to sustainable design is the need for an integrated delivery process that recaptures the integration of human–climate–place embodied by indigenous populations, the integration of nature–human ecosystems illustrated by Rachel Carson, and the integration of disciplines central to introducing buildings and communities that are truly regenerative.

Integrated Delivery Processes

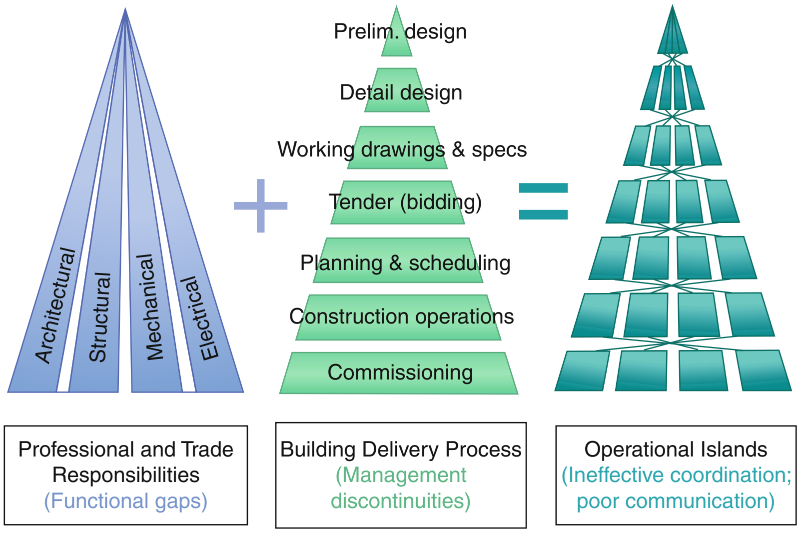
Legacy of a Fragmented Infrastructure

S.G. Mattar identifies the operational islands that exist in the building industry that contribute to ongoing performance failures in economic, environmental, and human terms [10]. By overlaying the functional gaps of increasingly multidisciplinary teams with the management discontinuities of sequential stages of the work, potential points of missed interconnectedness or disintegration are revealed. Integrated delivery processes, including the use of BIM as a tool, begin to coordinate the separate disciplines in the design stages and the trades in the building delivery process. Section "Integrated Delivery Processes" will illustrate first how the building delivery process is evolving to integrate the expertise of design-construction-management, and section "Building Information Modeling to Support Integrated Project Delivery" will illustrate how the design process is evolving to integrate the diverse expertise of the comprehensive design team (Fig. 3).

Lean Thinking as a Path to Integrated Project Delivery

In the Japanese language, the term for waste is *muda*, which is fundamentally based on an understanding value. In the world of lean manufacturing, at least seven types of *muda* have been identified: overproduction, waiting, transporting, inappropriate processing, unnecessary inventory, unnecessary/excess motion, and defects [2]. Further, lean thinking places value on the delivered product and its performance rather than just the cost of production, not unlike the concept of life cycle analysis as compared to simple first cost comparisons in the building industry.

Lean Production/Manufacturing Advances in the manufacturing world, specifically the automotive industry, provide context and insight into potential breakthroughs in the design and construction industry. In their book, *The Machine That Changed the World: The Story of Lean Production* [11], Womack, Jones, and Roos trace the history of production methodologies in the automotive industry, from craft production to mass production and most recently to lean production. In the mid- to late-1800s, craft production was the norm, characterized by a highly skilled workforce, decentralized organizations, use of general-purpose machine tools, and a very low production volume. In the early 1900s, Henry Ford introduced revolutionary changes to car manufacturing, thus beginning the era of mass production, coincidental with the aforementioned transformation of the design and construction industry's emerging reliance on technological innovation. As Womack suggests, it was not the assembly line that marked Ford's innovation, but rather "the



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 3
Fragmented infrastructure. These diagrams by S.G. Mattar in "Buildability and Building Envelope Design" illustrate the operational islands (opportunities for disintegration) in the traditional delivery model

complete and consistent interchangeability of parts and the simplicity of attaching them to each other."

Though considered to be a breakthrough in efficient product delivery, mass production held the same primary characteristics of building design and construction coming out of the Industrial Revolution, namely, "principles of specialization, division of labor, and standardization of parts to the manufacturing of goods on a large scale" [12]. Though considered to be a breakthrough in efficient production, costs of specialization within the workforce remained hidden. In yet another example of the dangers of specialization, Holstein explains:

▸ . . . the division of labor, the specialization of narrow skills, the detailed engineering specification of how each task is to be carried out, and the assemblage of large numbers of employees in great manufacturing plants have greatly diluted the identification of employees with their productive functions and with their employers. Many surveys in the United States and in the industrialized countries of Europe have shown that workers do not fully understand and appreciate their roles and positions in society. In addition, the division and specialization of labor may lead to such narrowly defined skills and highly repetitive operations, paced by the steady progression of a machine or conveyor line, that tedium and fatigue arise to reduce the sense of satisfaction inherent in productive work. [12]

As discussed under Future Directions, engaging mind, body, and spirit is also essential to understanding a truly comprehensive integrated delivery process, which is addressed in the lean production model.

By the 1950s, Eiji Toyoda and Taiichi Ohno at the Toyota Motor Company determined that mass production was an inappropriate approach for their organization, and so they set about on a different path, which would eventually become synonymous with lean production. Considered by many as the next significant organizational/production model, lean production finds its roots in an integrated approach to improvement. The mainstays of the Toyota Production System are "continuous improvement" and "respect for people," both of which suggest a strong reliance on integration within the process, the product, and the people creating them.

▸ "The key to the Toyota Way and what makes Toyota stand out is not any of the individual elements. . .. But what is important is having all the elements together as a system. It must be practiced every day in a very consistent manner—not in spurts." [13]

Though perhaps *revolutionary* in its conception, lean production is in reality a philosophy of *evolution*. It is an attitude toward innovation that is focused on continuous and incremental improvements, not in breakthrough transformations, or in essence multigenerational learning.

After in-depth observation of their processes in action, Liker derived 14 management principles that characterize the "Toyota way," all stemming from the fundamental commitment to "respect for people" and "continuous improvement" [13]:

I. Long-term philosophy.
   1. Base your management decisions on long-term philosophy, even at the expense of short-term financial goals.

II. The right process will produce the Right results.
   2. Create continuous process flow to bring problems to the surface.
   3. Use "pull" systems to avoid overproduction.
   4. Level out the workload (*heijunka*) (Work like a tortoise, not a hare).
   5. Build a culture of stopping to fix problems, to get quality right the first time.
   6. Standardized tasks are the foundation for continuous improvement and employee empowerment.
   7. Use visual control so no problems are hidden.
   8. Use only reliable, thoroughly tested technology that serves your people and processes.

III. Add value to the organization by developing your people and partners.
   9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
   10. Develop exceptional people and teams who follow your company's philosophy.
   11. Respect your extended network of partners and suppliers by challenging them and helping them improve.

IV. Continuously solving root problems drives organizational learning.
   12. Go and see for yourself to thoroughly understand the situation (*genchi genbutsu*).
   13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.
   14. Become a learning organization through relentless reflection (*hansei*) and continuous improvement (*kaizen*).

Liker cautions others away from rigidly applying these principles to their own organizations and encourages others to develop their own principles appropriate to their own situation, not unlike indigenous designs being culture based.

Lean Design and Construction Koskela, Howell, Ballard, and Tommelein [14] suggest that lean construction is both inspired and challenged by the theory of lean production. The Lean Construction Institute is an evolutionary framework of individuals and organizations (both theorists and practitioners) involved in a conversation on the application of this theoretical framework in the construction field.

Like lean production, lean construction seeks to eliminate waste while maintaining or adding value, a measure of productivity in product per man-hour. Data from the US Department of Commerce illustrate the decrease in productivity within the design and construction industry as compared to other industries in recent decades.

Those involved in the lean construction movement continue to explore the benefits of lean thinking on traditional design and construction processes. From its roots in production management, lean principles have been applied to and studied on large, complex, and short-schedule projects. Lean construction is a project delivery system that emphasizes the reliable and timely delivery of value. It does not hold the notion that there is a trade-off between quality, time, and cost on a project, but believes that all can and should be achieved. Significant to note is the fundamental difference between manufacturing and construction whereby construction is project/function based and site based, with each project unique by definition. Methodologies and/or tools that have been developed to work within a lean design and construction environment can be categorized into lean production management, lean design, lean supply, and lean assembly [15]:

Lean production management	Lean work structuring
	Scheduling
	Last planner system
	Look-Ahead Planning

Lean design	Cross-functional teams
	Set-based strategies
	Structured design work
	Optimization of design iteration
	Design production control
	Building information modeling (BIM)
	Communication flow protocols
	Big room
	Target value costing
	Reliable promising
	A3 reports
Lean supply	Communication flow protocols
	Information transparency
	Lean product supply
	Supply chain design and control
	Reliable promising
Lean assembly	Lean installation
	Continuous flow

In direct response to the fragmented infrastructure of the traditional delivery models in design and construction, the Lean Production Delivery System, as illustrated in Fig. 4, reconsiders traditional linear phasing of production with a more integrated approach of overlapping processes. Not unlike other fields, such as quantum physics, social modeling, and software networks, those studying lean design and construction have been recognizing the significance of interconnectedness rather than separation between individual components (Fig. 5).

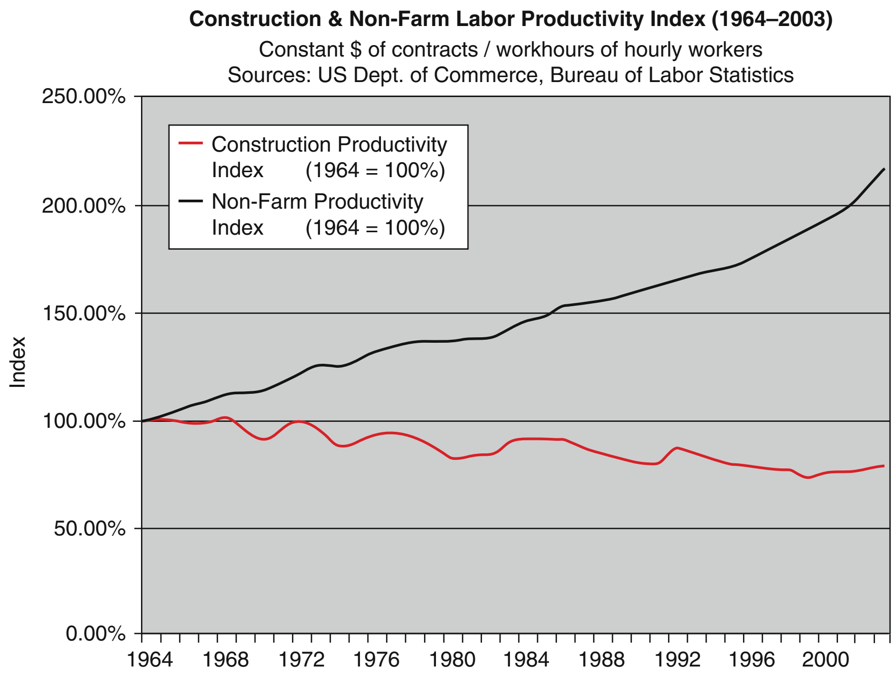
Integrated Delivery Processes

Integrated Form of Agreement In 2005, Sutter Health, a not-for-profit community-based health care and hospital system in California developed a contracting model that supports Lean Project Delivery [16]. This model was based on the research of the Lean Construction Institute, including an attempt to address management of workflow, team relationships, and contractual relationships. "Five Big Ideas" emerged as a framework that focused on the concept of maximizing value to the customer (in this case, Sutter Health):

1. Collaborate, really collaborate (throughout design, planning, and execution).
2. Increase relatedness among all project participants.
3. Consider projects as networks of commitments.
4. Optimize the project, not the pieces of the project.
5. Tightly couple action with learning.

Not unlike Toyota's lean production model, the foundation of an integrated delivery approach resides in a team's mutual trust and respect for the knowledge and expertise brought by each team member. For this reason, prior experience working together is a significant benefit, another access point to multigenerational wisdom. While collaborative skills of the team can be developed between newly congregated team members, intentional work is required upfront to build the mutual trust and respect and, therefore, take advantage of meaningful integration. Integrated project delivery is not simply getting everyone in a room together, but rather practicing a deep and significant collaboration of individuals, their knowledge and wisdom, and shared values – as suggested above by the first big idea: "Collaborate, really collaborate." Though not required to achieve integrated delivery, an integrated form of agreement as a relational contractual model can beneficially support this desired type of team behavior.

Integrated Project Delivery (IPD) In 2007, the American Institute of Architects (AIA) and AIA California Council introduced Integrated Project Delivery (IPD) as a "project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction." In this model, the multiparty agreement shifts dramatically from the traditional design-bid-build or design-build contracts to a focus on shared responsibilities for project delivery by the three primary players: owner, designer, and constructor.



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 4 Declining productivity. Data from US Department of Commerce, Bureau of Labor Statistics illustrating the decline in productivity in the design and construction industry as contrasted with other fields

Connection to Sustainable Design and Construction

A critical tenet of sustainable design is collaborative decision-making in the early design stages to ensure that preliminary decisions strategically support sustainability goals and do not compromise the ability of later decisions or actions in meeting those goals. Figure 6 illustrates the time and cost benefits of early design collaboration, with the promise of an even greater benefit of increased quality in the final building product.

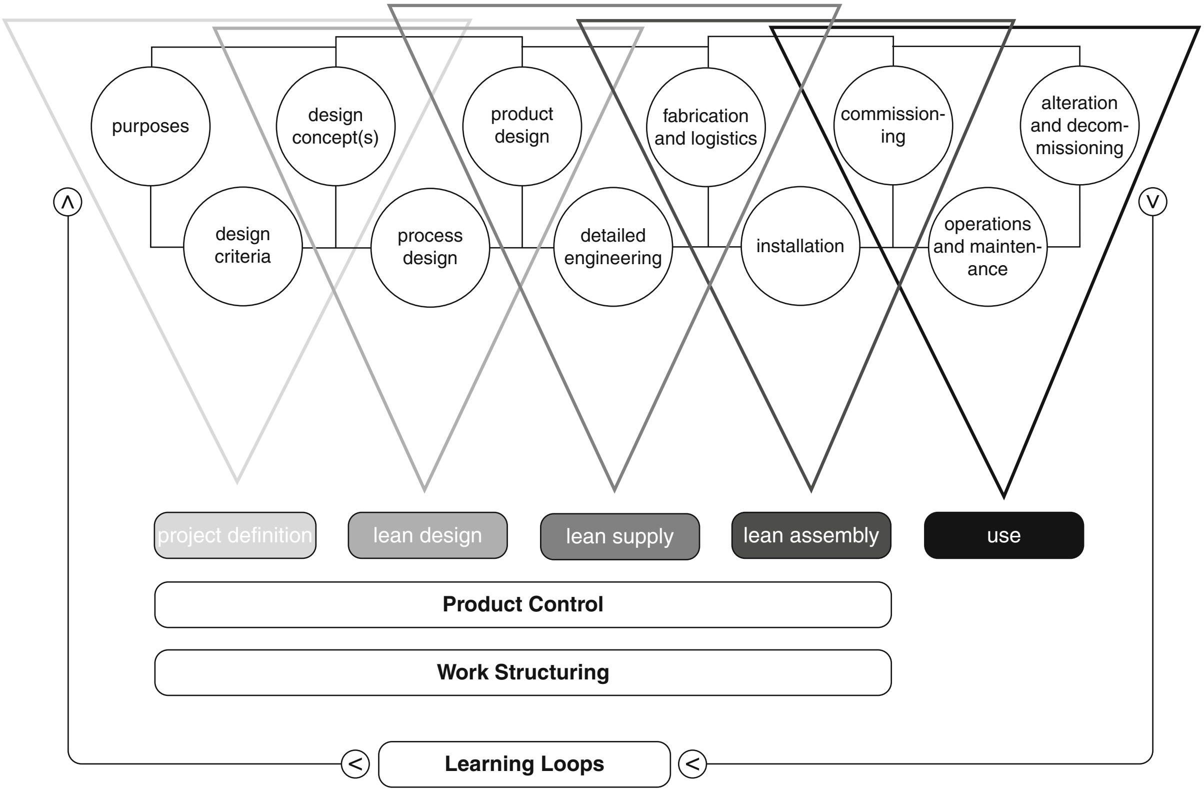
Numerous recent publications document the shift toward a more integrated approach in the building delivery process and the value of integrated design for high-performance buildings [17, 18, 19]. The changes in the building delivery process, especially with respect to when various project participants are brought on board, are illustrated in Figs. 7 and 8.

Since the introduction of integrated design processes, codified in LEED for example, the benefits to building performance and sustainability are just beginning to be quantified. Through integrated decision-making early in the design process, measurable gains in energy and water efficiency and material and land conservation have been recorded in new buildings, major retrofits, interior retrofits, and existing building operations [17, 19, 20]. The key is to *integrate, really integrate.* The advent of building information modeling as a mainstream design and construction tool is helping to facilitate an integrated team and therefore an integrated design process.

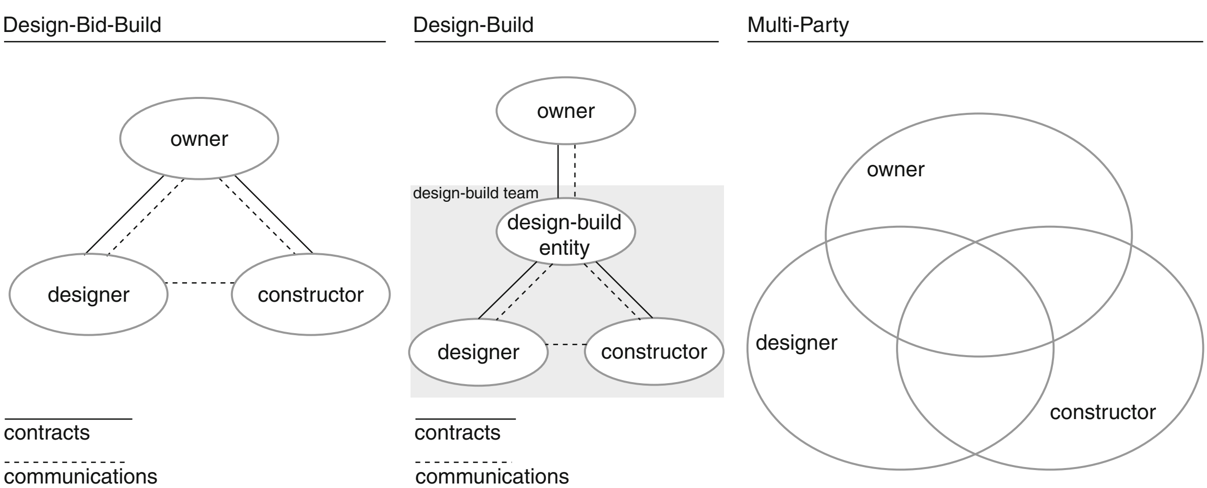
Building Information Modeling to Support Integrated Project Delivery

CAD to BIM

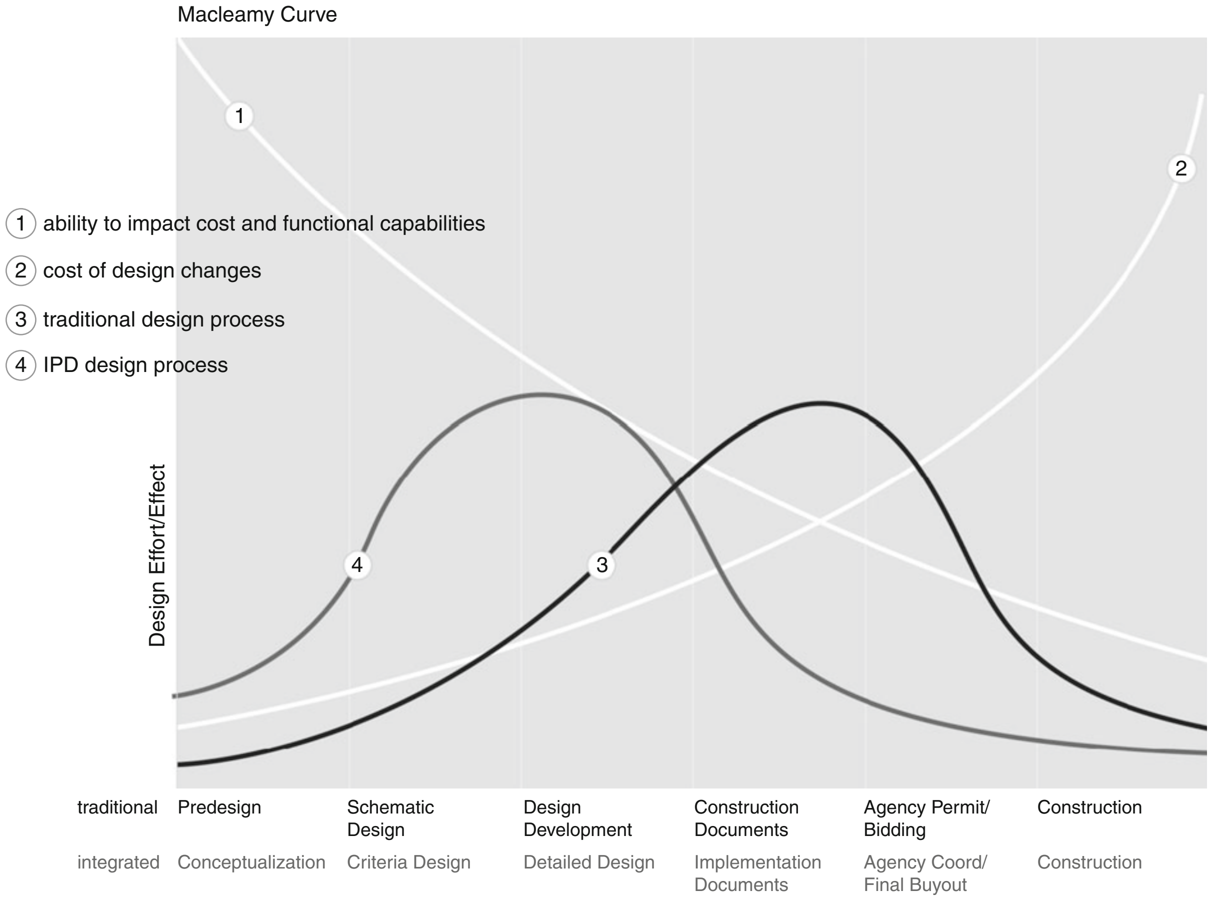
Building information modeling (BIM) moves well beyond traditional computer-aided drafting (CAD) by tying component properties and characteristics to a geometric model that supports parametric changes by each expert in the building delivery process. Parametric modeling takes its name from the project parameters or variables that are modified as work progresses. It also refers to the model's content as interconnected components and views, all of which are updated when modifications are made to one component in any view. Common in the shipbuilding, automotive, and



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 5
Lean project delivery system. From project definition through to product use, project phases overlap and a learning loop is introduced to reflect the goal of continuous improvement [21]



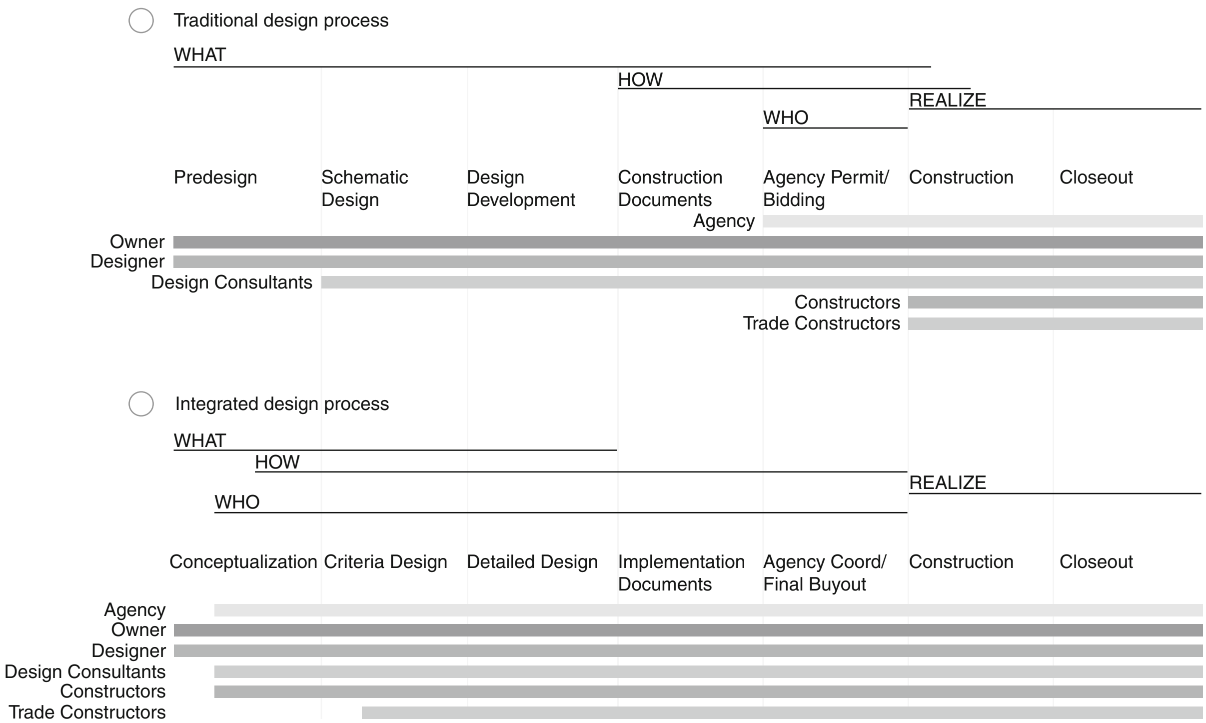
Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 6
Project delivery models. As compared with traditional delivery system models of design-bid-build and design-build, a multiparty relational agreement is one contract signed by owner, architect, and contractor (plus any additional key project partners), indicating the shared risk and reward nature of the relationship



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 7 The case for informed decisions in early design. Mcleamy Curve comparing design effort, project phase, and impact on costs. The implication of this diagram is that it is highly beneficial to the overall project success for key stakeholders to be at the table early in the design process making informed decisions

airplane industries for decades, the integration of parametric modeling within the architectural design process is relatively recent. With significant investment by software developers such as Autodesk and Bentley, BIM now supports integrated design development by architects, engineers, and contractors, generating as-built documents that can be updated and modified by building managers.

BIM in the Design Phase The most obvious benefit of BIM use in the design and construction industry comes in the form of three-dimensional design visualization. Three-dimensional models (be they physical or electronic) convey a better sense of the final project than two-dimensional representations of abstract views of the building. Site, floor, ceiling, and roof plans, and interior and exterior elevations are complex abstractions of the actual building, often unintelligible to those that need to understand them the most, from the client to future occupants. Three-dimensional models afford a much greater opportunity to understand the building during design before construction begins, when key decisions are being made. Not only is this beneficial with the client and user groups in making informed decisions, but it is also valuable in communicating the design intent to officials of regulatory agencies (code, zoning, public utilities, etc.), neighborhood groups, and any other stakeholders that would



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 8 Project team integration. Comparison of team member involvement for a traditional design process and an integrated design process as illustrated within AIA's integrated project delivery guide

benefit from fully understanding the project. So, in its most basic form, BIM affords real integration with the client and ultimate occupants/users of the building. As mentioned earlier, the full integration of these constituents in the overall process makes for a more integrated and ultimately successful solution.

To support an integrated design and construction team, another critical difference between BIM models and CAD models is the parametric nature of the model information. Because the model is being updated concurrently by various members of the design team, there is no lag time of sharing information between the various disciplines responsible for the design of the project. Also, discrepancies within the separated two-dimensional drawings of the building are also minimized. Design options can be rapidly generated for study and review to afford quick and informed decision-making, and to ensure that the latest decisions are communicated to the entire team. Cost estimating and construction review can occur iteratively and quickly (reminiscent of rapid prototyping or small batching in the lean world), rather than waiting until a benchmark set of documents is produced.

Manufacturers and trade partners, including curtain wall, mechanical, electrical, plumbing, furniture, and other manufactured products, have the potential to contribute key information regarding constructability and cost implications during design. The use of BIM in the design stage supports a level of iterative and early collaborative decision-making that is critical in the integration of the more rigorous design goals for sustainability.

BIM in the Construction Phase Contractor input is becoming a valuable component of the design process at times contributing to early design decision-making, cost estimating, and constructability assessments, pulling construction planning up into the design phases. In some instances, the BIM model is further used by the general contractor as well as trade partners for staging and sequencing, and as an effective communication tool to "see" the construction workflow in advance. Clarity of this kind of information eliminates waste at multiple levels, from early interference checking to the timing of on-site construction equipment (tower cranes, etc.) – allowing team members to coordinate their work effectively.

A highly beneficial feature of a BIM model is its capacity for interference checking. When all of the building's systems – structure, enclosure, mechanical, plumbing, and others – coexist in the same three-dimensional space, the team can collectively and virtually see space constraints and interferences, sometimes called clash detection. This is impossible without integration of multiple disciplines and without cultural integration of project team members from the owner, design and builder teams. Resolving such conditions virtually rather than out in the field eliminates waste at multiple levels – in time, materials, and cost. The economic, human, and environmental costs of change orders are significant, and integrated design practices combined with the use of BIM have the potential to measurably reduce these costs. This process blurs the line between design and construction phases as design modifications are made ahead of construction as informed by physical/construction realities.

BIM in the Manufacturing Phase Reducing short-term or long-term costs, however, is not ambitious enough for the sustainable design community. There is a long-standing and built-up need for improving installed performance of integrated systems, with the least amount of resources, which might also be enhanced through BIM. When the design team's BIM model is developed with the manufacturers and fabricators (direct to fabrication), an iterative "design assist" model is initiated, similar to lean design. Instead of fabricators redrawing the design documents and submitting for approval (in the traditional delivery model), the fabricator takes over the BIM design model or one portion of it and makes adjustments for improved performance for the design team to review and approve for fabrication.

Kieran and Timberlake's explorations in "refabricating architecture" are a vivid illustration of this approach [22]. In this model, BIM geometry and data are sent direct to fabricators for off-site fabrication or manufacturing in controlled environments where tolerances and performance can be optimized. In lieu of on-site *construction*, on-site *assembly* is maximized, shortening overall construction time and improving quality of workmanship. The migration of BIM models into the CAD/CAM arena offers significant gains in integrated design decision-making across the professional disciplines and through the building delivery process.

BIM and Building Performance Simulation As discussed in Chap. X, BIM models are beginning to support building performance simulation directly. Thermal, lighting, acoustic, structural, energy, and other performance simulation models have been advancing rapidly over the past decades. However, in almost every case, these models have needed independent geometric and performance specification profiles to be built in customized computer models before the simulation could be completed. Today, we see the first instances of the direct use of BIM models for performance simulation. Since geographical coordinates are resident in most BIM models, solar access and sunshading studies can be performed directly. More extensive modeling for daylighting and energy studies still requires separate interfaces, but progress in the interoperability of software packages is gradually allowing the original BIM model to be exported directly to the analysis software. This is especially true for energy analysis software in early design when a broad spectrum of options are generated and when comparative analysis and quick turnaround times are needed. As the design develops and more detailed material and component specifications are required for real projections of energy use or natural ventilation effectiveness for example, the interoperability of software still needs development.

Beyond energy simulation, BIM models can be instantly mined for area and material calculations to support the planning of other sustainable strategies, such as rainwater harvesting, material savings, and recycled content [23]. Interoperability advances beyond spreadsheet calculations are still needed, however, as will be discussed in Future Directions.

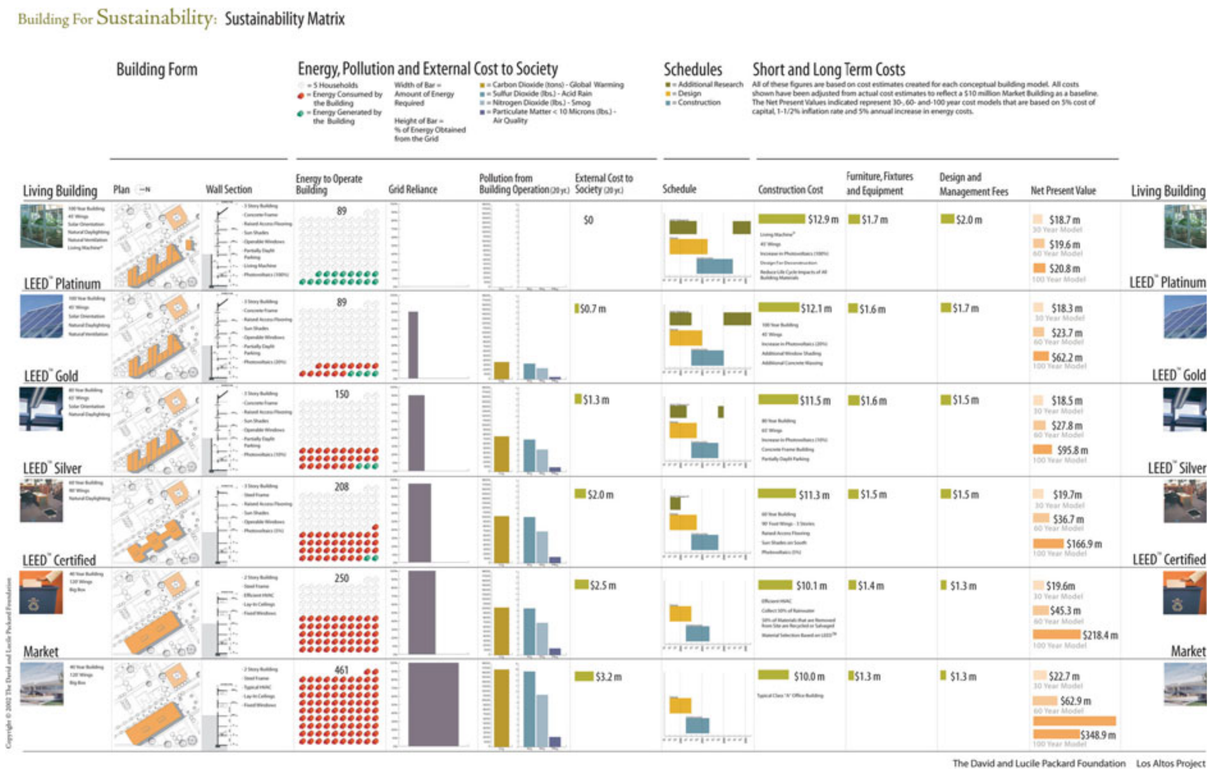
BIM and Materials Life-Cycle Cost Analysis (LCA) While BIM is often perceived to be simply a three-dimensional model, it has the capacity to accommodate additional dimensions by addressing systems integration in 3-D, design-construction-use phasing in the fourth dimension, performance outcomes in the fifth, costing, and more. One of the more important yet complex opportunities for building information modeling is the incorporation of material life-cycle properties. Wall, door, hardware, finish, and window schedules are all generated and updated automatically as the model is built with carefully chosen component libraries. Additional information about project materials embedded in the model – from raw materials to assembly and transport, from physical properties of components to those of assembled systems – would be even more helpful in iteratively assessing LCA impact of design decisions. The most immediate benefit of this database is the ability to report out material quantity takeoffs normally handled by a contractor or cost consultant. In addition to pure quantities, material qualities can also be embedded in the model. To ensure that manufacturers offer reliable and clear specifications for these BIM libraries, national standards are being created by the National Building Information Model Standard (NBIMS) Project Committee, under the National Institute of Building Sciences (NIBS) *buildingSMART alliance*™ with a broad constituency of industry partners [24]. As the material and product specification libraries become populated with reliable data, the design and construction teams will be able to make more environmentally sound decisions, driven first by simpler goals of recycled content and recyclability, cost, and physical performance (or durability/life expectancy). In the near future, as the inventory is populated with data about the full life cycle assessment of components, decisions for the most sustainable built environment will be better informed. Insert LCA criteria figure

The David and Lucile Packard Foundation Sustainability Report and Matrix is an early tool developed by the BNIM project team for a new headquarters building in Los Altos, California. It reflects an extensive study in understanding not only the first costs of sustainable design and construction but also long-term (generational) cost benefits, examined over 30-, 60-, and 100-year cost models [25] (Fig. 9).

BIM and Computer-Aided Facilities Management (CAFM) CAFM is a communication and tracking tool for ongoing operations and maintenance of a building and assets inside it, such as fixtures, furnishings, equipment, and people. To consider that the building information model has expended, its usefulness at the time of construction completion is to miss a significant opportunity for further integration of the BIM model into the project delivery process as it relates to its stored data. As noted in a 2004 NIST study on the costs of inadequate interoperability in the facilities industry:

- Owners and operators have the largest interoperability costs of all the stakeholders: over $10.6 billion, or about 68 percent of the total $15.8 billion of inadequate interoperability costs calculated for the capital facilities supply chain . . . This is because owners and operators carry the burden of ongoing interoperability costs during the operations and maintenance phase. . . Eighty-five percent of owners and operators' interoperability costs are incurred during the operations and maintenance phase. Quantified costs were estimated at approximately $9 billion in 2002. Although inefficient business process management costs are significant during this phase ($1.6 billion), the costs related to facilities management and maintenance are even larger. [26]

In an attempt to address these losses, use of the project's BIM model for facilities management, once the owner or tenant has begun occupancy of the building, is emerging. Activities such as employee tracking (moves/adds/changes) and asset management (spaces, equipment, furniture) are being handled within CAFM systems, yet it is rare for the BIM model that was built during design and modified during construction to be carried through to the facility management phase. BIM holds the component information for building materials, systems, and components, while CAFM holds the ongoing operations and maintenance information. The current goal in bridging this interoperability divide is the successful communication between in asset knowledge (BIM) and asset maintenance (CAFM). Similar to the development of compatible software for daylight and energy modeling that seamlessly accept appropriate data from a BIM model, bridging the BIM–CAFM means allowing the BIM and CAFM models to directly influence each other via data transfer, data such as manufacturers data on building materials and systems, including fixtures, furnishings and equipment



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 9 Packard sustainability report illustrating long-term financial impacts. The project team evaluated six conceptual designs for the same building program, each representing various levels of sustainable design and construction, including Market, four levels of LEED, and a Living Building. The 30-, 60-, and 100-year cost models were developed to demonstrate the long-term benefits of sustainable thinking

(especially mechanical), and the subsequent history of ongoing maintenance.

Workflow Transformation

Advancing sustainable design with integrated project delivery and building information modeling requires a traditional project team to fundamentally change the way the work is performed. Traditional sequential relationships between architects, engineers, manufacturers, contractors, and facility managers are eliminated, as teams rely on each others' expertise throughout the entire process to ensure higher quality outcomes. When project goals are met, all team members benefit, including the owner. When projects encounter unforeseen conditions or when oversight errors occur, the team solves the problem together rather than wasting energy determining fault. A full client and building delivery team is at the same table early in the process and collectively accepts risks and responsibilities for the entire project (see Fig. 7). Performance goals are set, and building design processes are established collectively to ensure integrated decision-making and collaborative problem-solving required to meet those goals. (See HPBDP outline.)

Architects, engineers, manufacturers, and builders are working within the same BIM environment to ensure the virtual building is coordinated prior to work on-site. To ensure high-performance buildings, critical building science consultants are engaged from project kickoff, participating in the generation and evaluation of design alternatives. The collaboration is fundamental because the integration of diverse ideas and feedback is critical to a more sustainable process and product. If the call for a truly sustainable built environment is real, this kind of fundamental transformation in how the design and construction industry works together must also be real.

Future Directions

Toward Interdependence

In the spirit of learning from indigenous cultures to help western civilization regains its connection to nature, reference to the term "ubuntu" from the Bantu language group is appropriate. This term has been translated in variant ways, all with the common thread of interdependence – one among others rather than one separate from others. Its simplest translation – "I am because we are" – suggests a fundamental understanding of self as inseparable from community. This embodies the spirit of what has been lost in our culture and what is required to achieve true sustainability of humanity and planet. This first principle of interdependence underpins all conversations on sustainable design and integrated delivery.

Connecting Data and Decisions

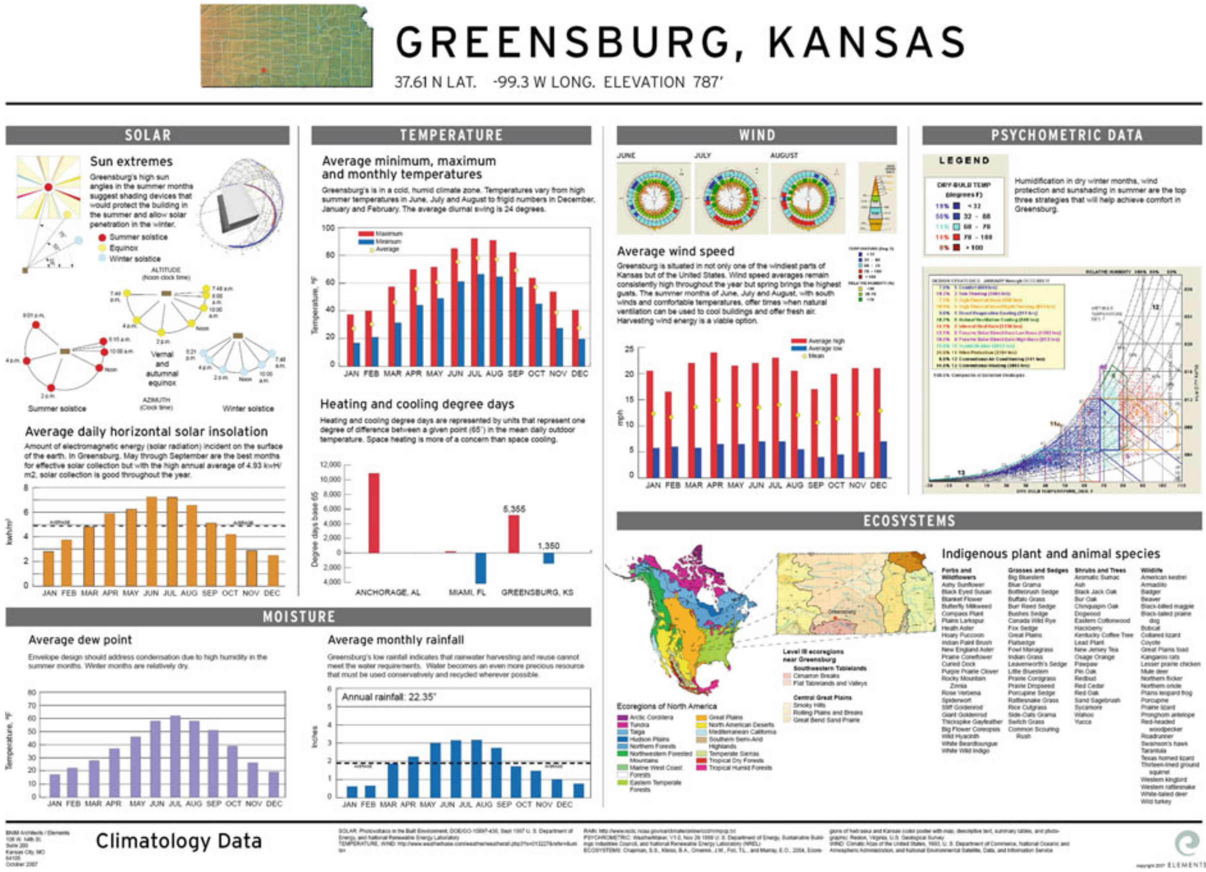
There are some basic and solvable ways that integrated practice, and building information modeling can be enhanced from its current forms to catalyze project teams toward better decision-making. On the one hand, strong benefits are gained by a project team that engages individuals who are local to a place – who bring some measure of historical wisdom and/or knowledge – particularly if that knowledge is multigenerational. Similarly, in-depth research on the environmental and ecological characteristics of a place is invaluable to design efforts geared toward true sustainability and restoration (Fig. 10).

Other solutions are technological in nature and solvable over time. BIM software is available today that alerts teams when a design is in conflict with local codes and ordinances. BIM parametric data can provide the design team with live LEED documentation as the design evolves – not all credits yet, but those that are dependent on quantities and dimensions, such as the percent of occupied spaces that have seated views and access to daylight. BIM models tie material data to product specifications, which support pricing models and alert the team when LEED material credits are met. These are all highly beneficial uses of a BIM model to automatically and parametrically calculate design-related performance outcomes as the design evolves.

Critical to the next generation of parametric modeling is the ability of the model to be located in time and space in order to support extensive data acquisition from external sources. As a project model is initiated, project site parameters would immediately connect live external data to the project. Imagine a model that pulls detailed data regarding rainfall expected at a project site – not just annual rainfall, but data from the last 100 years of rainfall, providing the team with trends in high and low years and potential expectations based on a more global understanding of climate change. Imagine a model that is linked to a product database that monitors product data and availability within close proximity to the site, or that identifies appropriate building systems or materials based on the project location. Imagine a model that, once "placed" within its geographical coordinates, identifies not only expected solar access and informs the team on appropriate orientation, massing, and sunshading, but also pulls available data on solar products and calculates anticipated solar income available at the building based on the efficacy of those products. The potential of BIM models to support data and analysis input from a diverse set of sources begins to bridge the sustainability gaps previously described, but only the technological gaps.

Reconnecting Nature and Human Nature

Integrated design practice methodologies and BIM tools have emerged to challenge and transform the "old" way of thinking. It is not clear, however, if they will be adequate for understanding nature's principles of interconnectivity and interdependence or for actively contributing to this regenerative loop. Native cultures throughout time have spoken out on the wisdom of nature and have given warnings against ignoring her interconnectedness, or "consilience" as E.O. Wilson would suggest [27]. John Muir left us with his observation, after spending extended time in the wilderness, that "When we try to pick out anything by itself, we find it hitched to everything else in the universe." Similarly, the David Suzuki Foundation, in preparation for the 1992 United Nations Earth Summit in Rio de Janeiro, issued their own Declaration of Interdependence [28], one they hoped would be adopted by all (italics mine):



Sustainable Design and Construction, Integrated Delivery Processes and Building Information Modeling. Figure 10 Climate data chart. A sample collection of basic environmental data collected for work in a specific locale. Primary categories of data minimally include solar, temperature, wind, psychometric data, moisture, and ecosystems (Courtesy of BNIM/Elements)

► **DECLARATION OF INTERDEPENDENCE**

This we know

We are the earth, through the plants and animals that nourish us.

We are the rains and the oceans that flow through our veins.

We are the breath of the forests of the land, and the plants of the sea.

We are human animals, related to all other life as descendants of the firstborn cell.

We share with these kin a common history, written in our genes.

We share a common present, filled with uncertainty.

And we share a common future, as yet untold.

We humans are but one of thirty million species weaving the thin layer of life enveloping the world.

The stability of communities of living things depends upon this diversity.

Linked in that web, we are interconnected — using, cleansing, sharing and replenishing the fundamental elements of life.

Our home, planet Earth, is finite; all life shares its resources and the energy from the sun, and therefore has limits to growth.

For the first time, we have touched those limits.

When we compromise the air, the water, the soil and the variety of life, we steal from the endless future to serve the fleeting present.

This we believe

Humans have become so numerous and our tools so powerful that we have driven fellow creatures to extinction, dammed the great rivers, torn down ancient forests, poisoned the earth, rain and wind, and ripped holes in the sky.

Our science has brought pain as well as joy; our comfort is paid for by the suffering of millions.

We are learning from our mistakes, we are mourning our vanished kin, and we now build a new politics of hope.

We respect and uphold the absolute need for clean air, water and soil. We see that economic activities that benefit the few while shrinking the inheritance of many are wrong.

And since environmental degradation erodes biological capital forever, full ecological and social cost must enter all equations of development.

We are one brief generation in the long March of time; the future is not ours to erase.

So where knowledge is limited, we will remember all those who will walk after us, and err on the side of caution.

This we resolve

All this that we know and believe must now become the foundation of the way we live.

At this turning point in our relationship with Earth, we work for an evolution:

from dominance to partnership;
from fragmentation to connection;
from insecurity to interdependence.

Important to note is Suzuki's final imperative that we work from "insecurity" – not to "security" but rather – to "interdependence," suggesting the stronger alternative to just security.

In a similar fashion, Benyus [5] provokes the designers of today to reconsider their source of inspiration and to look deeply into nature to find the "genius of place," the "biological beginning." *Biomimicry* – a call to study and absorb nature's principles for the purposes of design – is the other side of Carson's *Silent Spring* coin, a call in response to the warning. In it Benyus identifies a new science that views nature as model, measure, and mentor, searching for wisdom instead of knowledge to inform innovation in agriculture, energy, textiles, medicine, computation, business, and architecture.

Reconnecting Mind, Body, and Spirit

While it may be unorthodox to incorporate the notion of spirit within a scientific text, it is precisely the separation of spirit from mind and body that has distorted our thinking and has taken humanity out of alignment with nature. To underscore the need for integration, or reintegration in the case of the twenty-first century condition, one must reengage the spirit.

Chrisna du Plessis, at the first national convention of the US Green Building Council in 2002 in Austin, Texas [29], shared what the developing world can offer the rest of humanity in terms of sustainable thinking:

- In lieu of mastery of nature, consider mastery of self.
- In lieu of progress above all, consider humanity above all.
- In lieu of pursuit of knowledge, consider pursuit of wisdom.

As technology such as BIM bridges the knowledge gap, humanity's recognition of our own interdependence with nature can bridge the wisdom gap, leading us back to an integrated whole: the integration of man–climate–place honored by indigenous populations, the integration of nature–human ecosystems honored by Rachel Carson, and the integration of diverse disciplines central to introducing buildings and communities that are truly regenerative.

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Sustainable Heating Ventilation and Air Conditioning

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Article Outline

Glossary

Biomimicry Imitate or use models found in nature as inspiration for designs and processes to solve human problems. Nature becomes the measure by which a designer assesses the rightness of a design.

Green building High-performance building designed to be less resource intensive, have a lower environmental footprint, and reduce the life cycle environmental impacts of the material used.

HVAC The tools and technologies that heat, ventilate, and air-condition buildings to provide healthy and comfortable indoor environments.

Hybrid ventilation Mixed mode building systems that use natural ventilation when feasible and supplement with mechanical systems when not, either sequentially or simultaneously. Hybrid ventilation combines the best features of natural ventilation with mechanical systems.

Indoor environmental quality (IEQ) The quality of air inside the built environment.

Living building A net-zero building conceptualized as a living organism, integrated within a living system and having a positive impact on that system, including energy, air, water, and waste.

Natural ventilation Cooling and ventilating through design choices that permit outdoor airflow. Natural ventilation plays an important role in low-tech building design and seasonal strategies to reduce energy.

Net-zero buildings Buildings that not only achieve extreme levels of energy efficiency but that supply their own sources of energy on a net annual basis through renewable energy resources. The first goal is to reduce loads and maximize efficiency and then to provide for all of the rest of its energy requirements through on-site, nonpolluting, renewable resources.

Order-of-operations thinking The idea that by doing things in the right order, the engineer of sustainable HVAC can ensure the best fit between performance and cost. The first step is to reduce loads – to conceptualize a system that requires less heating and cooling to begin with. The second step is to utilize free energy resources like natural ventilation and passive solar. Step three is to select efficient and appropriately sized systems.

Regenerative design Regenerative design goes several steps beyond sustainability, encouraging the designer to participate *as part of* nature instead of acting *upon* nature. While net-zero buildings neutralize the impact of the built environment on the planet, regenerative design systems have a positive impact, often on a community scale.

Right-sizing systems Designing HVAC systems that are tailored to a specific building, at a specific time and place. The move toward downsized systems that fit the job.

Sustainable building Often used interchangeably with green building but with an emphasis on longer term and broader goals.

Thermal mass The ability of a material to absorb heat and re-release it later, using external energy to change the temperature of a high-density material such as concrete, or a material that absorbs and releases heat through phase change. Thermal mass plays an important role in low-tech building design.

Whole systems thinking Understanding the built environment as an organism, a coming together of interrelated elements instead of a series of discrete and separate parts.

Definition of the Subject

Sustainable HVAC is the collection of tools, technologies, techniques, practices, and methodologies

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that heat, ventilate, and air-condition buildings with minimal consumption and environmental impact. Sustainable HVAC seeks to find ways, through integrated thinking, to minimize and reduce the capacity of primary heating/cooling and energy-moving equipment in order to achieve the low energy, zero energy, and increasingly "energy plus" buildings of tomorrow.

Introduction

Commercial and residential buildings are an enormous drain of energy, consuming almost 40% of the annual US primary energy and 70% of the annual electric power [1, 2]. Green buildings, by contrast, are designed to be less resource intensive, have a lower environmental footprint, and reduce the life cycle environmental impacts of the materials used [2]. The enormity of the environmental footprint associated with the built environment means that engineers, whose work critically shapes that footprint, have a unique responsibility to practice sustainability [3]. Sustainable heating, ventilating, and air-conditioning (HVAC) prioritizes energy efficiency and low environmental impacts in creating the tools, technologies, techniques, practices, and methodologies that heat, ventilate, and air-condition buildings. Sustainable HVAC is part of broader systems, decisions, and practices that together constitute a successfully designed, constructed, and operated building. In essence, sustainable HVAC is a complimentary and supportive strategy to sustainable communities and buildings.

The HVAC field emerged at a time when society began expecting a controlled, predictable, and comfortable interior environment within which to live, work, and play [4]. From this expectation, the perceived need for human-made solutions to control or condition buildings arose. From the origins of Victorian-era heating and plumbing systems to warm buildings to the advent of air-conditioning and elevators which allowed buildings to be compact and comfortable in ever-denser urbanized environments, various systems, equipment, and methodologies have emerged and become defined as "standard practice" in the twentieth century.

The roots of sustainable HVAC are not new. In 1923, "Ventilation: A Report of the New York State Commission on Ventilation" [5] analyzed a variety of systems in New York schools with a view to determining the healthiest and most productive system at that time. The members of the commission included doctors and academics as well as Dwight. D. Kimball, a practicing mechanical engineer. The study concluded "...that window ventilation (i.e., natural), with ample direct radiation, window deflectors and adequate gravity exhaust, seems the most generally promising method of ventilation of a classroom, where conditions permit" [5, pp. 529]. Almost a century later, this is still a definitive volume on the subject and its early and enduring importance, and demonstrates that "hybrid ventilation" has been a system of interest for almost a century.

During the pre- and post-war eras, the move toward urban density, especially in the world of commercial and government office space, led increasingly to a typology of buildings with deeper floor plates and increased distances between occupants and sources of daylight and natural ventilation through windows [4]. The preeminent architectural boom of the 1950s and 1960s effectively led to a new norm of sealed buildings, relying entirely on artificial systems regardless of geographical locations. This defined a new "standard" for the time which influenced other building types and ultimately global building practices. Regional and cultural variation diminished [6]. In effect, an international standard had emerged during a period of prosperity and cheap, abundant fuel.

The oil crisis of the 1970s began to reframe and change ideas and attitudes within this industry as both the cost and certainty of energy came into question for the first time in the modern HVAC era [7]. From this point forward, various pressures were exerted on the notion of standard practice. Energy efficiency became a topic of interest as both the cost and security of fuel was no longer certain. The challenges of the 1970s continued in the 1980s when concerns emerged regarding the depletion of the ozone layer, attributed in large part to the commercial refrigerants of the day. In the 1990s, amplified concerns emerged around climate change and the direct link to CO_2 emissions from the use of fossil fuels to provide the higher quality of life demanded in developed and developing economies. Throughout these decades, the costs and environmental consequences of standard HVAC approaches were being scrutinized as were the levels of service required or even appropriate.

Today, a new paradigm is emerging where engineers are increasingly asked to optimize, minimize, downsize, or "right-size" systems and equipment, catering them to a specific purpose, in a specific location, at a specific time or day or year [8–10]. The profession has undergone a meta transformation, entering a new millennium where HVAC has shifted from a language of capacity (peak heating, peak cooling, etc.) to a language of consumption (kwh/ft^2 t CO_2/person). Sustainable HVAC has become a critical requirement of the industry today.

Sustainable HVAC seeks to find ways, through integrated thinking, to minimize and reduce the capacity of primary heating/cooling and energy-moving equipment in order to achieve the low energy and increasingly net-zero energy buildings of tomorrow. Ultimately, in a world of finite resources and fixed constraints, the engineer/designer must open their minds constantly to new ways of making building systems more efficient while having less of an impact on the infrastructures and environments that supports us.

Fundamentals

Understanding Context

When considering system choices, sustainable HVAC begins by understanding context. No two buildings or system solutions are the same. Instead, the designer should begin by asking the following key questions:

- Why is the building needed; for what purpose now and in the future?
- Where is the building to be placed geographically, given the nested contexts of surrounding buildings, communities, and natural or urban environments? Is it a single structure or one of many?
- What functions and sub-functions will the building perform? In asking this question, it is most effective to break the building down into its subcomponents: transient spaces, fully occupied spaces, and partially occupied spaces, and set standards and energy targets for each.
- When is the building used (by space, by time of day, by season)?
- Who will occupy and manage the building? Are the users permanent (as in the case of a government office) or transient (as in the case of a hotel)?
- How will the building be operated and by whom? Do you need to allow different operating strategies and system choices?
- What are the desired goals for the building now and over time? How do these goals vary from the owner/users perspective as well as from the city or state perspective on the building stock in 10, 20, and 50 years? Is there in fact a specific goal for the building (the tallest, greenest, quietest, etc.)?

By fully imagining the place the building will occupy, the designer can carefully consider all of the unique issues that may affect system requirements and performance. Both internal and external environmental factors are important. Contextualizing the building externally is critical: Temperature, humidity, wind, rainfall, solar energy, air quality, vegetation, and surrounding topography are all key. Each of these issues needs to be understood hourly, daily, seasonally, and annually to maximize natural benefits and deals with natural constraints. Hard data on climate variations is readily available from public data sets published by national weather data sources. The more subtle factors of site and building responses to variations in the natural environment also need to be understood (i.e., deciduous trees shed leaves in winter allowing increased solar radiation and wind which could benefit or hinder a design).

Internal environmental demands are also important: What the space is being used for (i.e., is it a building for machines, such as a data center or microelectronics factory or is it a building for human comfort)? What are the space needs and purposes? Who will occupy the space (now and in the future)? When and why is it being built (or increasingly renovated)? This will determine the desired indoor environmental quality (IEQ) and the acceptable ranges for air temperature, radiant temperature, humidity, air movement, air cleanliness, light, acoustics, and more [11–13]. Being able to imagine future use and users means imagining seasonal clothing patterns, desired access to nature and views of nature, permanent vs. transient occupancy, and the importance of the ability of an occupant to control their environment.

This may seem obvious, but its importance cannot be overstated. The system needs of a building hinge upon the specific contexts of that building. For example, a world class art collection might require highly controlled and largely artificial systems to ensure the preservation and protection of the collection. Conversely, a seasonally occupied retreat camp for outdoor adventurers in mountain regions far from urban infrastructure may trigger a much more natural set of choices in harmony with nature. A hotel in a hot, humid climate should be quite different than one in a temperate location, independent of the standard of service expected by the owner/user.

Considering these external and internal environmental factors will maximize the potential for sustainable HVAC. For example, two approaches could be taken to a three-story office building in a suburban Midwest location: First, a fully air-conditioned, code-compliant building with roof-mounted HVAC and sealed windows; second, a two-story courtyard design with operable windows and a hybrid system using decentralized geo-exchange heat pumps. Among the many differences these two choices would reveal, beyond more or less energy at the source, is the consideration of more or less noise from external HVAC equipment to the surroundings. Internally, the ability to operate/control local ventilation via operable windows supplementing or replacing active systems offers indoor environmental quality (IEQ) advantages. At the earliest stages of design, these impacts and differences need to be identified, discussed, and understood to enable the best decisions.

Developing Engineering Alternatives

The formal sustainable HVAC design process typically considers multiple solutions to a given design project: three or four architectural designs and the corresponding engineering choices and/or alternatives. This formality allows the designer and extended team to understand the implications both of architecture as well as engineering design decision-making.

When developing the alternative designs, there is a methodology that is common to each. All buildings can be separated into three types of spaces: passive; active/passive (or hybrid); and active. In some cases, a larger percentage of the building may be able to operate passively with the associated reductions in capital and operating costs. Conversely, some spaces may need to be fully treated with active systems. Most often, however, the solutions can come down to a combination of active/passive systems capable of operating differently depending upon season and occupancy.

Regardless of the split between these three approaches, a rigorous assessment and analysis of system requirements both physical and nonphysical (i.e., costs, energy, etc.) must be undertaken. In the case of passive or hybrid system design, it is especially important to consider the implications on comfort/operator interface. For example, a designer may choose to explore natural ventilation in an entrance area with low occupancies, but must anticipate occupant densities that are occasionally high. The design calculations must predict the increases in temperatures that are likely to occur and for how long. This allows the designer to engage in a dialogue with others and come to agreement moving forward with the notion of "informed consent."

A good place to begin in sustainable HVAC design is to identify an ideal design diagram to articulate the principles of what the engineer wants the building and systems to do.

For example, consider a building in a challenging inner-city site intended for a holistic health treatment center. The owner wants to use operable windows and natural systems, which they believe will be an asset to patient health. However, the adjacent streets have significant traffic and associated noise and air pollution, making an intuitive, simple, cross-ventilated section solution problematic. The problem is further compounded by the fact that the site is surrounded by large buildings which block sun and wind. Taking the ideal solution into consideration along with all of the elements of place and their attendant opportunities and constraints, the solution emerges: the creation of an inner courtyard which will become a green oasis and the "lungs" of the building. The courtyard will be used to draw clean air into the building both naturally and mechanically while the perimeter windows will be sealed to prevent dirty air and noise from entering. This system exemplifies a hybrid choice driven by an understanding of place together with a clear vision of the principles and philosophies guiding sustainable design. In this case, the methodology of interchanging the external and internal conditions iteratively led to the most logical solution.

Order-of-Operations Thinking Order-of-operations thinking is the idea that by doing things in the right order, the engineer of sustainable HVAC can ensure the best fit between performance and cost [3, 14, 15]. The first step is to reduce loads – to conceptualize a system that requires less heating and cooling to begin with. "Load reduction is the most powerful way to reduce the environmental footprint of a project (Macaulay and McLennan 2006, pp. 98)." Sometimes this means challenging preconceived expectations of clients and architects, and requires working with the design team in early phases to encourage architectural and siting choices that will ultimate reduce the heating and cooling loads of the HVAC system.

The second step in order-of-operations thinking is to find free energy resources [3]. Using natural ventilation and passive solar, for example, the engineer can harness the energy that is naturally available to heat and cool a building. As with step one, this requires the engineer to participate in design discussions at the outset.

Finally, step three in order-of-operations thinking is to select efficient and right-sized mechanical and electrical systems [3, 8–10]. Once the loads have been reduced and free energy utilized, the engineer can think about what systems should be designed to do the rest of the HVAC work of the building. The benefit of order-of-operations thinking is that by doing step one and step two, step three is often far less expensive and far more resource intensive than in mainstream engineering practice [3].

Integrated Design Process Sustainable HVAC benefits from participation in integrative design processes [3, 16–18]. As illustrated in the above discussion of order-of-operations thinking, sustainable HVAC looks for solutions in the earliest stages of building design. Finding ways to reduce loads and utilize free energy resources means being involved in discussions of building site and architectural design; it means having a stake in landscaping, structural engineering, urban planning, water management, and more. Sustainable design requires understanding the interconnections between all of the design choices for a building and its environmental and social contexts. Some of these relationships may be invisible at first and a single designer cannot possibly grasp them all. "Since no one has all of this knowledge individually, the role of the team takes on great importance in systems understanding [17, pp. 132]. Integrated design processes allow the engineer (and all other members of the design team) to find synergies early on that can maximize the sustainability of the building.

A key activity of the integrated design process is the design charette – a design meeting that brings together clients, engineers, architects, landscape architects, and other relevant disciplines or stakeholders to explore areas of overlapping and mutually beneficial solutions. The charette is inclusive, collaborative, and goal-driven [16]. It is often facilitated by someone whose investment is primarily in the design process itself rather than the ultimate product, and it brings in nontraditional expertise [16]. Each member brings their wealth of knowledge and research to the dialogue, applying it to the project at hand, with the intention of generating design opportunities for research and exploration [18]. "The ecological engineer embraces the charrette as the main engine for eco-innovation and integration that makes sustainability affordable and effective [3, pp. 97]."

LEED and Other Tools Green building rating tools are important assets for ensuring sustainable HVAC design. The increasingly standardized and third party verified tools provide a framework that can guide sustainable HVAC choices, reinforcing order-of-operations thinking in HVAC design. The most widely used rating system for green buildings is LEED (Leadership in Energy and Environmental Design), a point-based rating system that brings together diverse elements of a green building from materials and construction to water use to siting to energy systems and rates the degree to which that building has adhered to widely accepted standards of green building [19]. Developed by the US Green Building council and adapted for an ever-increasing number of situations and building types [20], LEED has been widely adopted in policy, building practices, and design.

Pursue Architectural/Engineering Integration

Unlike traditional engineering, sustainable HVAC encourages an actively symbiotic relationship between the architect and engineer [3, 21]. "The ecological engineer. . .realizes that unless the architectural process is understood and appreciated, then an optimized solution is not possible." [3, pp. 84]. Thus, once the context of the building has been determined and its implications understood, the sustainable HVAC engineer must consider architectural issues.

In early stages of the design process, the architect will be making decisions about site, orientation, density, and massing. These decisions are critical to order-of-operations thinking and will have a fundamental impact on the possibilities, constraints, and needs of the building systems. Architectural design is integral to sustainable HVAC engineering as well as a constraining feature.

The HVAC system requirements that result from architectural design decisions may, themselves, affect the architecture of the building. For example, a community college with low massing and shallow floor plates providing good access to daylight and operable windows may increase the cost of the perimeter envelope of the building skin, but reduce the sizes of mechanical rooms and distribution together with lowering the building's energy and emissions.

As a result, practicing sustainable HVAC design requires constant dialogue to balance architectural and engineering considerations throughout the design process. Engineers can explain the implications of primary architectural design decisions as they relate to system size, style, and first costs, as well as operating and environmental costs. Truly elegant architectural/engineering system integration is where you do not see the system itself and it performs at its optimal level discreetly.

Consider the choices of HVAC systems for a large international airport. The characteristics of the space are well known: Large transient populations in high ceiling open spaces; areas of peak gathering (i.e., ticketing and gates), and large areas of transient movement (halls, concourses). A conventional approach might be to utilize overhead ducts hidden behind acoustic ceilings high overhead. This approach uses large quantities of energy and system capacity to condition the occupied zone that is often more than 20 ft below the ceiling. Such an option is not, however, an elegant choice or one that integrates architecture and engineering. An alternative choice might involve decentralized localized conditioning equipment at floor level, integrated with TV screens, for example, and a largely passive conditioning strategy for the high volume above the occupants' heads, with roof relief vents and minor ductwork. Working with the architecture and furnishings often allows an efficient, cost-effective solution that results in lower energy consumption.

Philosophy

Sustainability demands a commitment to understanding the broad philosophical issues pertaining to buildings as part of communities and the broader built environment including infrastructure, transportation, the natural environment, and society itself. These philosophical issues demand a broader commitment from the design profession to defining and realizing bioregionalism, systems thinking, appropriate technologies, and innovations for sustainability.

Bioregional and Bioclimatic Thinking

Bioregional and bioclimatic thinking all but disappeared from HVAC design considerations in the last century along with the rise of the international/global standardization of building systems. The sustainable HVAC engineer must bring an understanding of bioregionalism and bioclimate back into design. This begins with the exploration of place: Where is the building? What are the natural characteristics of that place (temperature, humidity, highs, lows, averages, snow/rain/drought, wind intensity, and direction)? How does it vary by season? By time of day? Are there on-shore/off-shore winds to consider? Fog? Cloud cover? Sun? What kind of flora and fauna exist at the site? What is the natural vegetation and preexisting topographies? How have the traditional, vernacular buildings in that location been designed?

The importance of considering all permutations of place and its effect on systems cannot be overstated. For instance, sites in steep ravines will open up discussions of topographic sun shading and axial river winds unlike high desert sites with unobstructed skies and intense sun and wind. Large diurnal and contextual variations in environmental conditions may trigger diverse system choices to meet identical comfort or energy-performance goals for the two sites, even when they are in the same geographic region.

It is possible to find accurate weather data for most sites, but in cases where there are unusual microclimate conditions, local site testing is encouraged to fully understand challenges and explore opportunities. It is worth noting that the historic climate data that is relied on is no longer as predictable due to climate change, heat island effects, etc., so an ability to forecast future change is also needed.

Whole Systems Thinking

A fundamental philosophy underpinning sustainable HVAC design is "whole systems thinking." Whole systems thinking anticipates the interconnectedness of all things – natural systems, mechanical systems, social systems [22]. In green building design, whole systems thinking means understanding the built environment as a coming together of interrelated elements instead of a series of discrete and separate parts. Whole systems thinking allows the designer to deeply understand all of the attributes of the system and their implications and interrelationships. It also means using the health of the ecological system as a basis for design [17, 22].

Sustainable HVAC explores and discovers multiple layers of interconnections between energy flows, air flows, and water flows and looks for synergies to ensure use and reuse of resources flowing through a building and its systems. Whole systems thinking in sustainable HVAC utilizes an iterative approach to exploring these opportunities and tunnels deeper as the design proceeds.

For example, one approach to an office building in a cold climate might be to design a building with a code-compliant skin that incorporates a perimeter skin heating system for comfort. This is a classic example of linear, nonintegrated system thinking. By focusing only on one element at a time, this approach misses opportunities to make design choices that will have synergistic benefits across the system. Alternatively, whole system thinking might lead to spending more money to create a better envelope, switching, for example, from double to triple glazing, which would increase the insulation value *and* increase the surface temperature, allowing the designer to eliminate the hydronic system altogether saving both capital and energy. This whole systems thinking reflects what Hawkins, Lovins and Lovins refer to as "tunneling though the cost barrier" [15], the idea that active and passive strategies can be considered that may eliminate the need for entire systems resulting in large gains in efficiency and lower cost.

Prioritizing Low Tech, Optimizing High Tech

Traditionally, heating, cooling, and ventilation design was a matter of siting and constructing buildings in ways that took advantage of natural heating, cooling, and ventilation [4, 23]. It was not until the early decades of the twentieth century that totally artificial indoor environments became possible. Since then, the possibilities have grown exponentially and much of the history of modern HVAC is a history of technological innovation to achieve new and exciting possibilities in building systems. As illustrated in the discussion of order-of-operations thinking, sustainable HVAC turns these traditions on their head seeking simple, low-tech solutions before high-tech solutions.

At the heart of sustainable HVAC is the idea that wherever, and to the greatest extent, possible, design problems should be solved by using the natural benefits of air, water, sun, and shade. Designs that take advantage of natural ventilation [23], night ventilation, and thermal mass [24, 25] are important low-tech strategies for sustainable HVAC. Another important set of strategies stem from enhancing the building facades: appropriately specified and configured windows, sunshades, overhangs, trellises, awnings, and roofing can all be manipulated to support natural heating, cooling, and ventilation in a building [26].

In all likelihood, HVAC technologies will be added once the natural systems have exhausted their potential or to enhance the potential of the low-tech solutions. Sustainable HVAC has a plethora of cutting-edge solutions within its tool kit: underfloor air distribution, displacement ventilation, radiant heating and cooling systems, geo-exchange heat pump systems, thermal storage systems, labyrinth natural cooling methods [26–30], and more.

Yet even at this point, a commitment to prioritizing lower-tech solutions can lead to optimizing higher-tech solutions that remain sustainably focused. Increasingly, engineers are opting for mixed-mode buildings or hybrid ventilation using natural ventilation during times of the day, year, or use cycle that are feasible, and supplementing nature with building mechanical systems when natural ventilation is not feasible [31, 32]. Such strategies combine the best elements of natural ventilation with high-tech options. Technologies integrated into walls [33], roofs [34–36], and windows [37, 38] as well as attention to how these components are installed and interconnected [39] can facilitate and increase the efficiency of natural, low-tech conditioning.

Keeping simplicity at the forefront and engaging in critical, self-reflexive questions is essential to sustainable HVAC: Has this system been done before? If not, why? What measures are needed to mitigate or share risk? Who will operate and maintain the systems? How much user interface is needed or encouraged?

Asking these questions will maintain some of the benefits of low-tech solutions, even as higher-tech solutions inevitably come into play and result in a high-tech/low-tech hybrid that optimizes sustainability. As an illustration, a design team was exploring the introduction of a double facade to an existing downtown office building. The goals were to reduce energy while allowing the reuse of 70-year-old operable windows that had been fixed shut for two decades due to concern about noise and external pollution. The design team developed a scheme which allowed the original windows to be opened manually by the occupant again (low tech). They created a buffer zone via the double facade (low tech) and allowed air to come into the buffer zone at different levels seasonally through temperature sensors (high tech). The buffer zone was vented during hot summer days via fans with DC motors that were powered by DC PV panels directly (high tech). The balance of high-tech and low-tech solutions through whole systems thinking and integrated decision-making ensured that the project achieved the highest level of sustainability.

Innovation

Committing to low tech, passive conditioning and simplicity in high tech does not mean the abandonment of innovation. Indeed, it is essential to continue to search for innovation in sustainable HVAC and there are at least four categories of innovation that are critical to explore: tools, techniques, technologies, and timing.

Tools There are many recent innovations in engineering design and simulation tools for the sustainable engineer. Building information modeling supports integrated design. Energy Plus under ongoing refinement by the US DOE and the Lawrence Berkeley National Lab illustrates the advancement of building simulation tools that support accurate predictions of performance for hybrid HVAC systems. The advancement in measuring and predicting microclimate weather data provides increasingly accurate information for designing buildings that rely on natural energies. Modeling the ability of a building's potential to cycle energy in and out of thermal mass can reduce or even eliminate the need for mechanical refrigeration.

Techniques As previously discussed, the most dramatic shift in engineering techniques is integrated design. Integrated design ensures that all disciplines are engaged at the earliest design stage in decision-making, and establishes processes to ensure they remain engaged for critical decision-making as design develops. Other innovations in engineering processes include blurring the line between designing, building, and operating buildings to ensure the delivery of the highest sustained performance at the lowest cost. Building commissioning is becoming a critical service of the engineering profession, and in the future peer review of design drawings – a form of pre-commissioning by an independent expert – may also become the norm. Collaboration with industry to ensure the delivery of integrated systems that deliver sustained performance may replace the delivery of a series of independent technologies that may be difficult to integrate and operate effectively. The list of opportunities is substantial and global connectivity allows us to learn from each successful project.

Technologies Clearly, new technologies are allowing us to lower energy and resource consumption. Breakthrough technologies, however, are often expensive unless coupled with incentive programs or with whole systems thinking to change systematically how the buildings are designed and built.

Confidence in the market may be critical to allow the rapid uptake of these new products and a similar reduction in capital cost. Photovoltaics are a case in point. Initially invented for the exploration in space, PV panels became a choice for building renewable energy in the 1970s but were cost prohibitive for most buildings other than prototype demonstrations or pilots. A number of countries, states, and other jurisdictions began aggressive incentive programs, the most publicized and successful of which were in Germany and California. In Germany the approach was to give three times as much money for electricity sold back into the grid than the utility would charge to sell electricity (known as a feed in tariff). The factor of three to one makes the economics of purchasing the PV panels more lucrative on a life cycle cost basis, and has resulted in a shared public-private investment into substantial renewable energy for the country. Similarly, the state of California embarked on a utility incentive program that provided incentives and rebates to reduce the capital cost of PV panels installed in the state.

In both cases, the increase in volume of PVs required in the marketplace led indirectly to reduced costs for purchase, greater industry growth, and measurable creation of new energy sources. This trend continues on a global scale as the interest in renewables and particularly PV is driving up the volume of manufacture and down the price. Simultaneously, ongoing research and development is increasing the efficiency of the PV equipment as competitive forces drive the innovation cycle through mass market adoption.

Designers, however, must be aware of the consequences of introducing new technologies into a new market and build in resiliencies that ensure adequate training and ongoing technical support as needed. The global interest in "green technology" is exciting and will no doubt bring to market much needed new technologies (wireless control, advanced glazing, renewables, to name but a few).

Timing The introduction of innovation requires consideration of the timescale.

Sometimes a new product or system is available but the market – locally, regionally, or nationally – is not ready for any number of reasons: price, attitude, knowledge, public/private constraints, etc. However, since a building takes multiple years to be designed and built, "future pricing" will need to be factored in to make educated decisions regarding technologies which will be purchased years down the line. At the same time, long-term goals for sustainability must be determined: a minimum life cycle for materials and systems; energy resource goals with an eye to long-term costs; material resource goals with an eye to employment and regional strength; human health goals; and even survivability goals in the face of brown-outs and blackouts. Discussions about the lifetime of the building and its systems ensure that sustainability will be paramount.

Replication

It is often the case that sustainable HVAC designers looking to innovative solutions are thought of as inventors. This is an incorrect perception. Instead, it is the HVAC engineer's job to seek out new ways of solving problems through the use of innovative tools, technologies, and techniques and then to reuse them on a broader scale, through knowledge transfer within the industry. Efficiency is gained from the replication of successful design processes that in turn allow us to spend more time exploring new ideas of design.

However, the identification of "successful" designs does place a demand on the engineering profession to undertake post-occupancy evaluation, to ascertain the success of their engineered solutions for delivering thermal comfort, air quality, acoustic quality, and more.

The Human Factor

Designing HVAC systems to be sustainable is a very pragmatic goal. Buildings are tangible assets. They are designed, built, and operated by real people of various social, economic, and educational backgrounds. Addressing the requirements of all of the users is critical to bringing to life a well-functioning building. In the end our buildings must be practical, affordable, and enduring. A level of pragmatism should be used at every step of the process: Can this be done here and now? Are the right skills, tools, techniques, and training available? Can future operators and users manage these systems?

Not only are real people designing the systems, but importantly, real people will be operating them [40].

Research demonstrates that predicted building performance does not match actual performance in part because of the behavior of occupants and facility managers [41, 42]. Cultural, social, and economic factors can all shape how people will use building systems and how that may change over time [40, 43]. It is critical to anticipate how buildings will be used in real life and use that information in HVAC design decisions so that otherwise sustainable systems are not undermined by incorrect use, or that opportunities for user-based savings are not missed [44–48]. While there is an element of unpredictability to the behavioral effects on HVAC systems, models exist to guage human influence [49].

If people are seen as active participants in their built environments, providing and maintaining the conditions that they desire, instead of as passive recipients of predetermined comfort conditions, the demands for comfort itself can shift from energy-intensive HVAC to integrated systems that are more sustainable [41]. Ray Cole of UBC argues that conventional approaches to comfort which do not take into consideration behavioral aspects result in HVAC systems designed for predictability and uniformity rather than resilience and adaptability [41]. Research is demonstrating that human comfort in buildings is shaped by more than thermal, luminous, and acoustic conditions [41, 50] and that people tolerate and even enjoy a wider range of conditions than previously assumed [13].

Engaging building occupants in environmental conditioning requires clear and concise communication and feedback among building inhabitants, building managers, engineers, and the systems themselves. Several communications technologies have been developed to facilitate such ongoing interaction: dashboards, smart meters, mobile technology, and many others [41].

Future Directions

The applied science of HVAC has shifted from a system-intensive emphasis in the middle of the last century to a much more integrated combination of natural and artificial systems. The HVAC designer of the future should have a broad understanding of both high- and low-tech solutions as well as an understanding of the place-based, contextual, environmental, and human factors that allow particular system choices to be used.

Rating systems such as LEED and BREEAM have allowed decision makers to request, incent, and explore higher levels of environmental performance at similar costs and service qualities. Increasingly, sights have been set on producing net-zero buildings – buildings that not only achieve extreme levels of energy efficiency but that supply their own sources of energy through renewable energy resources [51–54]. Ideally, a zero energy building meets all its energy requirements through on-site, nonpolluting, renewable resources. As with sustainable HVAC overall, the first goal is to reduce loads and maximize efficiency and then to provide for the remaining needs with renewables.

In the future, there will be greater exploration of the potential of the net-zero approach at the level of communities [54, 55]. Understanding buildings not as isolated units, but as interconnected elements of larger built environments can ultimately reap even greater environmental rewards. The potential for net-zero design at the community and campus level, determining optimal ways to extend the conceptual boundaries of net-zero buildings, will most effectively utilize renewable resources globally [54].

As net-zero buildings move into the future, it is also important to consider not only operating energy but the *embodied energy* of a building – the energy necessary to deliver the products and services that are used across the life cycle of a building [56–59]. Originally, most definitions of zero energy buildings focused on operational energy rather than embodied energy. Hernandez and Kenny propose the net-zero building of the future is one in which the "primary energy use in operation plus the energy embedded in materials and systems over the life of the building is equal or less than the energy produced by renewable energy systems within the building" [56, pp. 819].

Some argue that net-zero buildings do not go far enough and that one should be striving for living buildings. A living building conceptualizes the building as a living organism, integrated within a living system [6]. The Living Building Challenge lays out advanced measures of sustainability for the built environment, working to diminish the gap between current limits and ideal solutions [60]. Through its seven performance areas: site, water, energy, health, materials, equity, and beauty, the Living Building Challenge provides a framework for design, construction, and the symbiotic relationship between people, the built environment, and nature.

Moving beyond carbon neutrality, the buildings of the future should actively participate in restoring and renewing natural systems [17, 22]. Regenerative design goes several steps beyond sustainability, encouraging the designer to participate *as part of* nature instead of acting *upon* nature [22]. If net-zero buildings neutralize the impact of the built environment on the planet, restorative and regenerative design actively engages and interacts with local earth systems to have a positive impact. Following principles of bio-mimicry, regenerative design seeks to use nature as its model and inspiration [6, 61, 62]. Nature becomes the measure by which a designer assesses the rightness of a design, asking, is there a precedent for this in nature? [61]. Constant feedback and ongoing learning allow the design to shape and evolve in concert with the natural systems of which it is a part.

Realizing the future of sustainable HVAC will require a constant thirst for curiosity and innovation to explore, define, and redefine approaches, methods, techniques, and technologies that will support the quest for a cleaner and healthier built environment: in pursuit of zero.

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Sustainable Landscape Design, Urban Forestry and Green Roof Science and Technology, Introduction

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A sustainable landscape is a healthy and resilient landscape that will endure over the long term, which can be achieved by including the five basic principles in landscape management: resource conservation, built development, environmental quality, social equity, and political participation. That means that in sustainable landscapes, ideally, humans and nature represent coevolving systems that interact within the bounds of the geosphere (including biosphere, atmosphere, pedosphere, hydrosphere, etc.) at various temporal and spatial scales and across scales – from the field to the region, or nations, continents, or even globally. The natural functions and ecosystem processes of the sustainable landscape are able to absorb disturbances, retain its basic functions and thus maintain themselves into the future. The need to achieve such sustainable environments in the future should be the driving force changing the way we live and work in the present and future centuries. Climate change and global warming, loss and fragmentation of habitats and biodiversity, decline in water quality and availability, pollution of the atmosphere and large-scale soil sealing, and salinization all point toward a need for behavior change in all sectors of our world. To feed our growing population, extensive agricultural use of the landscape is needed, which contributes to a large extent to some of these aforementioned environmental problems. But also urban landscapes are resource-hungry, requiring significant inputs of energy, water, nutrients, and chemicals while many of our plant selections and practices are unsuited to our environments. The result is all too often lush and green parks and gardens that are thirsty, hungry, deplete the soil, allow invasive plants to escape, use unsustainable materials, contribute to waterway contamination, and provide limited habitat for native fauna. To achieve landscape sustainability and to ensure a healthy future, especially agricultural and urban landscapes need to be more efficient in their use of resources and work with the given ecological and climatic conditions rather than against them.

But how to define sustainability for all the different landscape components mentioned – which dimensions have to be considered? How to measure it? And how should the sustainability of landscapes be evaluated? Which targets have to be set up and which thresholds should not be exceeded? What forms of landscape planning and governance structures exist and how far they refer to the goals of sustainability? And, should sustainability be achieved quasi "gratis" in case population declines? In this section, a range of highly experienced authors formulate answers to these fundamental questions.

Simon Bell (see entry ► Sustainable Landscapes) introduces the subject of the section: The subject of sustainable landscapes is a complex one because landscape as a concept includes not only the physical structure of the environment but also human perception. This latter, being subjective, means that values of landscape change from person to person, cultural to culture and over time. Thus, compared with a simpler subject such as air quality where there are objective measures of levels of pollutants, for example, what may be a sustainable landscape in one circumstance may not be in another circumstance at another time. This makes the future prediction of sustainable landscapes particularly challenging. Landscapes should be of great concern to most people. Landscapes may have many diverse values. For example, using the common approach of sustainability with the three "pillars," it may have an economic value as scenery for tourism, a social value as the place where we live and an environmental value as the human habitat providing water, food, and sustenance. Some of these values are placed fairly high in Maslow's hierarchy of needs. Therefore, they may not receive a lot of attention in parts of the world where food security, drought, or poverty are significant issues. But elsewhere they are important if not, as yet, satisfactorily taken into account in

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calculations of sustainability, mainly because measuring and valuing them is seen as to subjective and complicated. The contribution by Simon Bell shows that the subject is worthy of study and that it is an important factor in evaluating overall sustainability. One of the challenges is that the subject lies at the boundary of or overlaps with many other disciplines and that there is a risk of double counting some aspects when indicators of sustainability are chosen, for example. The main field where these values overlap is (landscape) ecology and the concept of ecosystem services.

When thinking about sustainability, it is mainly about how to keep intact nature and environmental resources for either future generation or, more in terms of environmental justice, for other parts of the world. Land use and spatial planning focus on how to minimize negative effects of urban and industrial growth. Set against this context, urban shrinkage represents a new challenge, *Dagmar Haase* argues in her paper (see entry ► Landscape Planning/Design of Shrinking Landscapes). This is true due to the fact that one has to deal with the opposite phenomenon of growth – population decline and accompanying processes of de-densification – which, unemotionally, also asks the same questions as even mentioned for growth: How can land use development be steered in order to ensure quality of life of the population under conditions of decline? How can high-quality and sustainable urban livelihoods be developed? Are there visions for sustainable shrinkage? Resource consumption is a problem particularly in cities due to the concentration of population – that is consumers of environmental goods and ecosystem services. Since some years, more than half of the world population lives in cities. And – what is more – more than 200 cities worldwide, mostly in Europe, Russia, Japan, and the USA, are shrinking: they lose population. Shrinkage and declining population numbers do not mean an automatic decrease of natural resources consumption such as land, energy, or water, because the per capita requirements on environmental resources, ecosystem services, and housing space are increasing. Also in shrinking cities household numbers increase. In consequence, population losses along with rising per capita housing space lead to further land consumption and enlargement of, e.g., transport and infrastructure. Also in shrinking cities sprawling settlement development continues because of specific housing preferences such as single family houses and spacious housing with backdoor garden. Since shrinkage does not follow the logics of growth, there are no receipts for how to sustainably develop or plan a shrinking city. The paper shows that shrinkage appears in many different shapes and argues that there will not be a "one-size-fits-all" or textbook-answer to this question. So doing, the paper addresses the relationship between urban decline, sociodemography, infrastructure, land use, and ecosystems and discusses causes and consequences of shrinkage in the light of sustainability. It ends up with showing how actors in cities react to shrinkage in terms of rethinking their visions, instrumental settings, and strategic planning.

Planning for biodiversity in the city to reconnect humans with nature will definitely be a topic for the twenty-first century which is discussed by *Robbert Snep* and *Philippe Clergeau* (see entry ► Biodiversity in Cities, Reconnecting Humans with Nature). Worldwide, the diversity of plant and animal life is diminishing at high speed. At the same moment, more and more humans become city dwellers, with both the proportion and absolute number of people living in cities increasing rapidly. An important link between global biodiversity loss and fast urbanization is the enormous ecological foot print by urban dwellers, the huge demand for natural resources as required by the urban life style. Besides, a generally less well-known impact of the global urbanization of human society is the extinction of wildlife experience. People in cities lack frequent and intense human-nature interactions, as compared to our rural history. This leads to a decreased understanding of and support for plant and animal life. This not only negatively impacts biodiversity conservation efforts; it also restricts the long-term abilities of humans to benefit from nature. By promoting urban biodiversity, nature will be enhanced in the direct living and working environment of citizens, enabling humans to reconnect with nature. The entry addresses the opportunities to enhance urban biodiversity and its experience by citizens. The authors illustrate how the city environment is perceived from a wildlife point of view, which is necessary to recognize opportunities to enhance urban biodiversity. Next, they discuss these opportunities one by one, illustrating with examples how to implement them in practice. The authors conclude with an exploration of future possibilities to integrate urban biodiversity conservation opportunities in the broader concept of sustainable city planning, design, and management.

Non-use and shrinkage produce brownfields which appear to be very heterogeneous and thus an experimental field for sustainable urban redevelopment. *Dieter Rink* and *Juliane Matthey* (see entry ► Urban Redevelopment and Quality of Open Spaces) therefore focus on urban redevelopment plans for shrinking cities. Such plans generally proceed on the assumption that an orderly and controlled retreat from extensive development is feasible. Vacated land is to be successively transformed (from the periphery inward) into new parks, woodland, or amenity green space. This is also expected to integrate peripheral settlements better into the surrounding landscape, improve the supply of open space, and contribute to new site qualities in the inner cities. One goal is to establish green corridors that serve both recreational and nature conservation purposes. In shrinking cities, however, redevelopment produces open spaces or brown field sites of various sizes practically everywhere in the urban fabric, smaller sites in inner-city old-housing areas as well as large areas in prefabricated housing estates through systematic demolition and downsizing. Many local authorities engage in scattered downsizing within existing settlements. But this type of urban redevelopment reaches its limits when "holes" steadily multiply and the physical urban fabric disintegrates. Redevelopment and downsizing raise the question of how the design of open and green space can provide a new quality of urban development. The authors see as one of the major challenges for the future is how public funding can best be deployed in handling vast areas of previously developed land within increasingly perforated cities, for example, as succession areas attractive to residents. This paper looks at the solutions already available and what contribution they can make to improving the quality of life in cities.

Martin Volk (see entry ► Landscape Planning for Sustainable Water Usage) deals with landscape planning for sustainable water usage. Extreme events such as floods, droughts, as well as water scarcity and poor water quality have been increasing globally during recent decades. Global change phenomena, increasing population density in some parts of the world, as well as multiple land use of landscapes such as agricultural management, urbanization, and industrialization are some of the main reasons for these problems. Both, the mentioned reasons as well as the resulting environmental consequences, represent some of the world's most pressing problems that occur on different scales – from the field to the region or even globally. In recent decades, integrated river basin and environmental management – including landscape planning – has been introduced as a potential but challenging instrument to tackle these complex transdisciplinary problems around the world. However, several problems still exist before an effective integrated planning and management can be realized. Volk's contribution introduces to these problems and presents contributions to the solution for some of these problems. Among others, promising developments of decision support systems are presented as one future direction to support sustainable land use planning and water resources management.

Henning Nuissl and *Stefan Siedentop* (see entry ► Landscape Planning for Minimizing Land Consumption) report on another crucial component of landscape sustainability directly related to its use: Land use driven environmental degradation has long been considered a locally scaled phenomenon. Today, the global dimension of land use related environmental change is generally acknowledged by researchers and policy makers. The need to provide a still growing world population with housing, food, fiber, and freshwater accompanied with wasteful land use practices has resulted in a cumulative loss of biologically productive land and ecosystem functions. Moreover, land use practices are directly or indirectly responsible for the chemical degradation of environmental resources and high levels of greenhouse gases. Thus, land use has become a more and more important agent of global change that influences fundamental environmental processes. In their contribution, the authors scrutinize the question that modern land use processes allow humans to increase the short-term supply of material goods but undermine ecosystem services in the long run on regional and global scales.

Within the "built environment" there are lots of potentials more than on green urban areas to change cities into more sustainable places. *Manfred Köhler* (see entry ► Green Roofs, Ecological Functions and

► Green Roof Infrastructures in Urban Areas) argues that, in recent years, there has been a growth in interest in natural green roofs, or eco-roofs, as distinct from roof gardens due to the ecological benefits that may be derived. Roof gardens were traditionally installed in many countries to provide amenity space and for building beautification, in places such as hotels and resorts. The ecological benefits that were derived such as thermal insulation were almost an afterthought. Nowadays, in many instances, natural green roofs are installed to become natural ecosystems in urban areas. The benefits achieved by such installations can be measured not only in the building itself but the surrounding urban area as a whole. Green roofs have been shown to mitigate the urban heat island effect.

Stephan Brenneisen and *Dusty Gedge* (see entry ► Green Roof Planning in Urban Areas) focus in their contribution on green roof planning in cities and urban areas. The authors argue that in the twenty-first century – the century of the (mega) city according to the UN – urban areas will increasingly need to be planned and developed to take in consideration of the ecological and environmental health of the urban clime to ensure cities can cater for people. This is also a pressing matter in as it is recognized that there is a need to adapt cities to the negative effects of climate change. These issues have been central the work of professionals in the field of green roofs over the last 20 years and increasingly the technologies and approaches of green roofs have been shown to have a positive effect on a number of issues facing cities and megacities in terms of ecological and environmental health and in helping cities adapt to climate change as they reduce the urban heat island effect, localized flash floods as well as air and noise pollution and increasing biodiversity in the urban realm. These processes are part of an evolving approach to planning referred variously referred to as green infrastructure or ecosystem services. Urban greening has therefore become an increasing important approach for planners and is likely to be one that will predominate in the future. It took a long time after Le Corbusier's first steps to the implementation of green roofs as an ecological measure to be absorbed into mainstream urban planning. Green roofs became more popular as a part of ecological construction in the 1970s, and in the early 1980s a number of cities implemented nascent strategic planning approaches to encourage the uptake of green roofs. Elsewhere a series of pilot projects were initiated to explore the ideas and approaches to green roofs in urban areas. The main drivers for the implementation of green roofs in the 1970s–1980s research also suggested that green roof provided a broad range of environmental benefits, such as energy savings, reduction in storm water runoff, and overheating, but there was also a recognition that green roofs also promoted health and well-being and were an essentially element in an "ecological" approach to construction.

Stephan Pauleit, Ole Fryd, Antje Backhaus and *Marina Bergen Jensen* discuss in their contribution on ► Green infrastructure and climate change the role of urban planning to mitigate climate change. Since by 2050 two thirds of the world's population will live in cities and, what is more, already today cities of the developed world are a major source of green house gas emissions, they need to make serious efforts to mitigate climate change. Urban planning can play a major role in this respect by designing compact, low footprint cities. However, climate change will also make a severe impact on cities mostly by intensification of the heat island effect, increase of surface runoff from more frequent and intense rainstorms and by coastal and riverine flooding. Urban planning will play an important role for development and implementation of integrated strategies for climate change mitigation and adaptation. Green infrastructure can assist in adapting cities to climate change by reducing the urban heat island effect and by managing stormwater runoff. Urban greening in form of planting of shade trees and roof greening can also reduce the energy demand for house heating and cooling. Therefore, design of the urban landscape will have a direct influence on mitigating climate change and the impact of climate change on people's livelihoods and assets.

Kjell Nilsson, Cecil Konijnendijk and Anders Busse Nielsen focus in their contribution on urban forestry and its importance for sustainability and human wellfare. Urban forestry has become defined as the art, science and technology of managing trees and forest resources in and around urban communities for the environmental, social, economic and aesthetic benefits trees provide to people. In its broadest sense, urban forestry embraces a multi-managerial system that includes municipal watersheds, wildlife habitats, outdoor recreation opportunities, landscape design, recycling of municipal wastes, tree care in general and the production of wood fibre as a raw material. Urban forestry includes activities carried out in the city centre, suburban areas and the peri-urban or interface area with rural lands. Urban forestry is a new and still developing research field. Growing awareness about the need for more integrated approaches to urban green planning and management, and specific threats to urban tree populations caused by pests and diseases (such as Dutch Elm Disease) led to its emergence in North America during the 1960s. Europe and other parts of the world followed with for example international research networking intensifying during the late 1990s. The concept of urban forestry as encompassing the planning, design, establishment and management of trees and forest stands with amenity values situated in or near urban areas, has become more widely accepted. However, urban forestry is an emerging and still developing field with great potential. Thus, sustainability issues in this emerging field of science and practice are of overall importance and thus found their place in this encyclopedia.

Sustainable Landscapes

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Article Outline

Glossary

Aesthetics The study of the nature, appreciation and meaning of beauty in the arts, architecture, and landscape.

Beauty The attractive properties of a landscape which occur when a diversity of elements are found together yet are in a harmonious association; the viewer moved emotionally by a scene of beauty.

Ecological aesthetics An approach to aesthetic theory based on the idea that nature is inherently beautiful and that the understandings of the dynamics of nature lead to a richer aesthetic experience.

Landscape A prospect of scenery that can be taken in at a glance from one point of view; an area of land as perceived by people whose character is the result of the action and interaction of natural and/or human factors.

Landscape assessment The process of describing, classifying, and evaluating landscapes.

Landscape character A distinct and recognizable pattern of elements that occur consistently in a particular type of landscape.

Landscape capacity The ability of a landscape to cope with increasing degrees of change without this leading to a change of its essential character.

Landscape design The process of creating a new landscape or modifying an existing one for a combination of practical and aesthetic purposes.

Landscape perception and preference The study of the way people see different landscapes and the reactions they have to them.

Landscape sensitivity The degree to which a given landscape could potentially be affected by possible changes, such as development, which may negatively affect its character.

Landscape value A measure of the different benefits obtained from a landscape. These may be future or potential values as well as those obtained in the present.

Personal construct theory An attempt to explain how people take information about their environment and construct a personal view of this, which becomes normative for them and thus a lens through which they see the world around them.

Place A way of looking at landscape as a location or behavior setting composed of the physical environment, activities, and perceptions.

Place attachment The way people feel connected to a specific location which may arise as a result of many factors, some concerned with the landscape. This may help to give people a sense of identity.

Quality of life The consideration of factors which affect various dimensions of our life and the way people feel. Environmental and aesthetic factors can increase or decrease quality of life.

The sublime An aesthetic sensation which arises when a viewer's senses are swamped by the magnitude of the scale of a landscape that is difficult to comprehend and which seems limitless.

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Visual capacity The degree to which a landscape can absorb additional new elements without appearing overloaded.

Visual sensitivity The degree to which different people are likely to be affected by changes in the visual environment as a result of development or landscape change.

Definition of the Subject and Its Importance

The subject of sustainable landscapes is a complex one because landscape as a concept includes not only the physical structure of the environment but also human perception [1]. This latter, being subjective, means that values of landscape change from person to person, cultural to culture, and over time. Thus, compared with a simpler subject such as air quality where there are objective measures of levels of pollutants, for example, what may be a sustainable landscape in one circumstance may not be in another or at one time when compared to another time frame. This makes the future prediction or modeling of sustainable landscapes particularly challenging.

Landscapes should be of great concern to most people and they may have many diverse values. For example, using the common approach of sustainability with the three "pillars," landscape may have an economic value as scenery for tourism; a social value as the place where people live; and an environmental value as the human habitat providing water, food, and sustenance (see Fig. 1). Some of these values are placed fairly high in Maslow's hierarchy of needs [2] and therefore may not receive a lot of attention in parts of the world where food security, drought, or poverty are significant issues. But elsewhere they are important if not, as yet, satisfactorily taken into account in calculations of sustainability, mainly because measuring and valuing them is seen as too subjective and complicated.

This article explores this complex subject and demonstrates that it should be taken into account as seriously as other, more objective measures. It will show that the subject is worthy of study and that it is an important factor in evaluating overall sustainability. One of the challenges is that the subject lies at the boundary of or overlaps with many other disciplines and that there is a risk of double counting some aspects when indicators of sustainability are chosen, for example. The main field where these values overlap is ecology and the concept of ecosystem services.

Introduction

All landscapes, whether urban or rural, mainly natural or intensively managed constantly undergo change. This is normal and cannot be halted, especially when natural geological and ecological processes take place, let alone cultural, economic, and social changes that cause pressures for land use change and development [3]. Throughout the world, land use and landscape change are ever present forces, but they act at different rates and in different ways in different places. Urbanization, leading to urban sprawl, is a widespread phenomenon receiving much attention at the present time

Sustainable Landscapes. Figure 1
This landscape in Wester Ross in Scotland has many values to different people – economic (as a source of income from agriculture, fishing, tourism or forestry) social (as a place to live) aesthetic (it is an attractive scene) and for recreation/tourism (it provides a contrast from everyday urban life and a place to escape from stress (Source: Simon Bell)

Sustainable Landscapes. Figure 2
A landscape in the south west of France near Lectoure, Gers, of intensified agriculture where many older landscape features, especially small woodlands, have been removed and the amount of arable cultivation has increased as a result (Source: Simon Bell)

and it is a particularly significant process in developing countries – over half the world's populations now live in cities and these cities frequently expand with no planning or organization and create appalling conditions for the life of those forced to live there. In rural areas, which still make up by far the greatest proportion of the land surface, even in densely populated and urbanized areas such as Europe, change is also widespread. In 1995, the European Environmental Agency identified seven factors that have an impact on land use and landscape and which, 15 years later are still present, though to different degrees in different places [4]:

- Intensification of agriculture (Fig. 2)
- Overgrowth of agricultural lands (Fig. 3)
- Urbanization and development of infrastructure (Fig. 4)
- Standardization of building materials and designs (Fig. 5)

Sustainable Landscapes. Figure 3
An example of an abandoned field in the Vidzeme region of Latvia where the land is overgrowing with trees and bushes. This is a common sight in the Baltic countries (Source: Simon Bell)

Sustainable Landscapes. Figure 4
Urbanization is proceeding at a fast pace in countries like China. Here in Hangzhou massive areas of multi-story housing are being constructed (Source: Stephan Pauleit)

Sustainable Landscapes. Figure 5
Standardized designs create anonymous landscapes. This housing estate happens to be in a small town in Scotland but the houses could be built in any town or city in the UK (Source: Simon Bell)

- Tourism and recreation (Fig. 6)
- Excavation of mineral resources and establishment of landfill sites (Fig. 7)
- Disappearance of natural biotopes, habitats, and ecosystems, in part as a result of the above factors

The drivers of these changes are social and economic. Social factors include demographic changes, such as lower birth rates and increasing life expectancy leading to an ageing society in developed countries; higher birth rates and increasing life expectancy leading to population pressures in developing countries; migration of people within countries (from rural areas to the cities) or between countries, or from one continent to another. In the case of European and other rural areas, this is tending to lead to rural depopulation, especially by the out-migration of younger people which leaves a declining number of increasingly older people left in the countryside [5]. There may also be countertrends (in developed countries), such as when urban people move back to the countryside, perhaps at retirement, or to live while commuting to the town for work, or even to work there (telecommuting). This process is known as "gentrification" of the countryside as people bring urban qualities and expectations with them, which leads to the landscape becoming a place

Sustainable Landscapes. Figure 6
Tourism development places enormous pressures on the landscape. In the Bavarian Alps ski resorts and associated infrastructure can be significant elements in the scene (Source: Simon Bell)

Sustainable Landscapes. Figure 7
Mineral excavation can affect large tracts of the landscape. Oil shale extraction, Aidu Mine near Kohtla-Nõmme, northern Estonia (Source: Simon Bell)

for living in instead of living from. There may even be migration at retirement when people move to countries or regions with better climates and lower living costs, such as Americans from the north-east moving to Florida or British and Dutch moving to Spain [6] (Fig. 8).

Economic changes may drive some of the social changes – such as low farm incomes causing people to seek higher wages in urban areas, or high unemployment leading people to move abroad for work. Economic drivers, such as the need to keep costs down or the need to keep up with technical advances, drive intensification and the use of standardized equipment or infrastructure which results in a reduction of landscape diversity and regional character.

Political influences, such as repressive regimes, civil war and unrest and poverty also lead to migration pressures and refugee flows as well as changes to populations where identity with land and landscape may be part of the problem causing the unrest, such as nationalism or religious/cultural competition. All

Sustainable Landscapes. Figure 8
An example of landscape change due to the construction of ex-urban housing developments to meet the demand of international retirement migration from the UK and the Netherlands to Alicante region of Spain (Source Ingo Zasada)

Sustainable Landscapes. Figure 9
A marginalized rural village and landscape in north-east Portugal, in the Montsinho Natural Park, where only old people are left behind (Source: Simon Bell)

these factors cause changes to land use and landscape, and the movement and displacement of people has significant effects on their attachment to and relationship with landscape.

The two main land-management trends in rural areas are marginalization and intensification which both have an impact on the landscape and its visual- and biodiversity [7]. Marginalization is a feature of developed countries with stable and urbanized populations and may lead to land abandonment as farmland is no longer considered viable to maintain in cultivation and no one wishes to continue managing it (perhaps because the younger people have moved away and there is no one left to manage it) (Fig. 9). This may lead to the loss of cultural landscape elements as traditional features and practices are no longer to be found, such as haymaking or hedge management or the husbandry of local animal breeds. Often it is also traditional knowledge about management, use of local foods and crafts which die out in such circumstances.

Intensification is usually accompanied by larger-scale activities in bigger fields, more inputs, such as

Sustainable Landscapes. Figure 10
The remains of a collective farm from the Soviet times in Latvia, now collapsed and abandoned. The Baltic countryside is littered with such ruins (Source: Simon Bell)

fertilizer and pesticide, and use of more and larger machinery so that output per employed person is much higher and fewer workers are needed per hectare. Equipment, buildings, and other infrastructure tend to be larger in order to deal with the increased scale. Traditional field patterns, small-scale biodiversity elements, and traditional buildings usually do not fit into the new large-scale patterns of production, so that these tend to disappear. As a result, the landscape becomes homogenized and loses its regional or local identity.

The relative impact of these two processes varies from country to country and region to region according to basic factors, such as terrain, soil type, climate, and distance to markets, so that in the regions with multiple disadvantages marginalization is likely to be greatest and vice versa.

The value of traditional cultural and biodiversity elements in the rural landscape has not gone unrecognized in some regions, and policies for conserving important features have increasingly been supported through mechanisms, such as agri-environment schemes, aimed at reducing the intensity of agriculture and protecting or restoring important landscape features in Europe, for example [8].

Putting a historical perspective on the role of change in the rural landscape [9], it can be seen that there have been many examples of major landscape changes, most of which were the result of initiatives by landowners or other powers at the time. A prime example of this is the enclosure movement of England and parts of north-west Europe in the eighteenth and nineteenth centuries which transformed large-scale open landscapes into geometric hedged fields, and in so doing displaced a large proportion of the rural population and caused many of them to move to the towns and cities [10, 11]. The settlement of the American West in the nineteenth century and the division of land using the survey grid not only transformed the landscape but also the population and culture of a huge territory [12]. Collectivization of agriculture in the Soviet Union is another example of major landscape change undertaken by the power of the time which had massive social consequences (such as famine in Ukraine in the 1930s and deportations of so-called “kulaks” or better-off peasant farmers to Siberia) [13]. Although collectivization has been abandoned, the relics of the infrastructure still litter the countryside of many areas of the former Soviet Union as shown in Fig. 10.

In the development of the discussion on landscape and sustainability, some authors identify two main approaches or “schools” [14]. One is the protection, management, and design of scenic assets, and the other concerns ecosystem services and human well-being [15]. The main profession involved in landscape planning, design, and management, that of landscape architecture, also approaches the subject from two directions: one direction is planning, through the application of processes for evaluating and protecting or managing landscape change in rural areas in order to obtain or maintain scenic and/or cultural benefits while the other direction is the creation of low-impact but socially inclusive design for urban and residential areas. These two aspects need not be mutually exclusive since developments in valued scenic areas may be acceptable only if designed to be low impact.

This entry explores the meaning and understanding of landscape from several perspectives and follows this with consideration of what gives a landscape value and how to describe and define the many facets of value that may exist. This is followed by an assessment of what sustainability in a landscape means and how it can be evaluated and tested. Some examples highlight the possible application of sustainable landscape planning, design, and management at different spatial scales.

Landscape

The concept or definition of landscape has been discussed in many places and means different things in different contexts [3]. The word in English, originating from German and Dutch words such as *landschap* originated in the idea of the land being created or molded. The word landscape itself originates in an old German word *lantscaf*. *Scaf* became the English word "shape" and the German *schaben* or *schaffen*, so that, for example, the current German *Landschaft* means land that has been shaped (by man) [16]. In English the influence of Dutch landscape painting on British art and landscape appreciation has led to the development of the Oxford English Dictionary definition as "a prospect of inland scenery that can be taken in at a glance from one point of view." This is clearly a very visual definition and relates strongly to landscape paintings seen from a single point, but has also become associated with the single viewpoint overlooking a spectacular piece of scenery. In terms of the valuation of special landscapes and the designation of protected scenery, for example, this concept has been important, so that many of the national parks around the world are in spectacular mountain areas, such as Yosemite in California, the Grand Tetons in Idaho/Wyoming (see Fig. 11) the Rockies in Canada or the Lake District in England.

In other languages, the word for landscape may vary in its origin and the meanings it carries, perhaps deriving from words associated with "land" or with "views." In some cases, it is borrowed from other languages and may or may not carry the original meaning. For example, in French the word for landscape is "paysage," which is derived from the word for land or countryside, "pays," while in Russian the word for landscape when the physical land and its planning are concerned is "landshaft," borrowed from German, but

Sustainable Landscapes. Figure 11
A scene of the Grand Tetons seen from the Idaho side of the national park, where the traditional definition of landscape as a prospect of scenery is evident – in this case providing a sense of beauty and possibly the sublime (Source: Simon Bell)

for a landscape painting the word "paysazh" is used, borrowed from French.

This visual definition of landscape in English is also reflected in the literature on aesthetics, where this external, visual experience may be capable of invoking in the observer a sense of beauty or the sublime [3]. The alternative approach, known as the "participatory aesthetic" [3, 17], involves the person experiencing it using more than just the visual senses and being in the landscape, living there, perhaps, or having to travel through it in order to experience it – as it is not visible all at once from a single viewpoint. This tradition suggests that instead of the landscape experience being a special one – the view from the mountaintop – an aesthetic experience is part of the normal, everyday experience of the world around us. Thus, in a country where the countryside is composed of areas of farmland, farmsteads, lakes, rivers, and towns set in a forest, for example, the experience of traveling around, following the winding roads, continuously opens new small-scale, enclosed scenes which quickly change from moment to moment – there are no grand vistas – and frequently provide charming vignettes of the landscape. The same applies to wandering round the winding streets of a medieval city where small squares and glimpses into courtyards provides a rich experience as shown in Fig. 12. If the participatory aesthetic is a viable theory, it makes sense that people living and working in the landscape or visiting it on weekends are sensitive to the changes taking place and are concerned by them. Aesthetic quality of the landscape becomes an important value and not a merely cosmetic, superficial aspect affected by the whims of fashion and taste [3].

The second approach to the definition of landscape is in the ecological literature. In this landscape is primarily a definition of scale [18] somewhere between a region and a site or biotope. The idea of scale relates well to the original definition of landscape as the prospect of scenery – what can be seen from a mountain or hill top is a certain area of land midway in size or scale between a region and a site. The landscape in this definition is composed of the elements of patches and corridors of different vegetation or land use, possibly set within a matrix – a land mosaic (see Fig. 13).

Recent approaches have emphasized the ecological landscape as being in a constant state of change – the mosaic patterns being affected by a range of natural and human processes which operate over different time scales [3]. Of particular relevance to the landscape of many countries are the human processes of land abandonment and the natural processes of colonization by forest, or the cutting of the forest and its secondary succession. Both these sets of processes have impacts on the environment – not only for animal habitats but also for the human habitat. Thus, a landscape ecological approach also has to consider the human dimension and cannot only focus on natural aspects – human shaping of the ecosystem has taken place as long as people have been using land, although the rate and scale of human-caused change may be at its greatest and having the most impact today. However, since the

Sustainable Landscapes. Figure 12
When exploring the winding streets of an old city such as here in Genoa in Italy, all the senses are engaged in the aesthetic experience. As well as the sights there are sounds and smells and the feeling of heat and cool, twisting and turning and the feeling of the pavements under foot (Source: Simon Bell)

Sustainable Landscapes. Figure 13
The ecological definition of landscape – a large territory in the Rocky mountains in Colorado with different interconnected section, in this case prairie, forest and alpine montane habitat (Source: Simon Bell)

ecological aspect is also linked with ecological sustainability and the notion of ecosystem services, this definition and all it implies will not be discussed further in this entry.

The third approach to defining the landscape is in the geographical literature, primarily arising from the field of cultural geography. Here the landscape is seen as the manifestation of all the interactions of people with the land and thus part of the means by which identity (personal, group, national) is created. In this respect landscape is an ideological concept: people have an imagined relationship with land and nature and this provides a lens through which they see themselves and the world itself [19]. Other writers note that landscapes are both products of culture and also create or recreate culture [20]. It is worth noting how landscape can play a major part in memory and how key landscape elements – rivers, mountains, or forests, for example – are highly symbolic of aspects ranging from nationhood to cultural identity [21]. That people have been shaping landscapes since they evolved from non-human anthropoid apes is not yet completely proven but certainly, since the start of colonization of large parts of the world commencing some 70,000 years ago [22], with the move of anatomically modern humans out of Africa, people have increasingly been major shapers of the landscape. It is no surprise, therefore, that geographers see the landscape first and foremost as a cultural artifact – a cultural landscape, formed by and reflecting back different cultures over time (see Fig. 14). Any landscape is therefore a *palimpsest*, where layers, or at least remnants, of past influences remain to a greater or lesser extent visible and continue to exert an effect on the character of the landscape.

Sustainable Landscapes. Figure 14
A cultural landscape in the Bordeaux wine-cultivation region in France where human activities contribute as much or more than natural factors to the landscape and its character (Source: Simon Bell)

The Council of Europe, in framing the Florence Convention (European Landscape Convention, ELC) chose to define landscape in cultural terms as “an area, as perceived by people, whose character is the result of action and interaction of natural and/or human factors” [1]. This is a very helpful definition not only for practical purposes by being clear and simple but also because it provides a common understanding for those countries which are signatories. The importance of perception in the definition is also significant, not only because it goes back to the first dictionary definition described above, but also because it is through perception that people see and identify themselves in relation to the landscape.

Thus, the landscape can be defined in terms of a combination of natural components, cultural layers, and aesthetic qualities. Landform, soil, drainage, and climate set the scene for natural vegetation potential. Upon this, and frequently acting at the same time, human activities of settlement, forest clearance, agriculture, urban, infrastructural, and industrial development have taken place to a greater or lesser extent (some landscapes remain predominantly natural in influences (see Fig. 15), others dominated by anthropogenic forces). Such human activity may have been planned over large areas and carried out at a single phase or carried out over time by a series of individual or collective actions steered by economics, technology, tradition, and cultural norms, within the limitations of geology, soils, and climate, by generations of farmers and other land managers. The landscape so created or evolved has certain aesthetic qualities; it forms a pattern of elements with particular shapes, colors, textures, and so on with a certain sense of unity and diversity. The landscape will also exhibit a certain condition (such as well managed or neglected) and be susceptible to different tendencies for change (such as land abandonment, agricultural intensification, or urban development). What is perceived by an individual is not only a snapshot at a particular time in its evolution, but the person perceiving it will consciously or unconsciously bring their own background knowledge, bibliography, prejudices, and experiences to it and view it in that context [23].

This integrated view of landscape is important for the rest of the discussion presented here. It involves exploring the evolution of the landscape – a particular landscape (or landscapes) within a particular country. It is seen by people from different cultural backgrounds and from different generations, who have many different experiences. They have certain attachments or associations with a given landscape and are sensitive to its condition and how it is likely to change.

Sustainable Landscapes. Figure 15
A view of the Grand Canyon National Park where the natural components, are tending to dominate over the cultural ones – more likely to be the case in the USA than in Europe. In this case the forces of erosion have produced an awesome structure which dwarfs human activity (Source: Simon Bell)

Landscape Value

The landscape, using the definition above, has many values to many people – economic (timber and farm produce, mineral extraction, real estate, scenery bringing tourists to an area, etc.); ecological (habitat value for many species, corridor functions, ecosystem services, such as flood mitigation, etc.) and social/cultural/aesthetic/spiritual values (as a place to live, as a place for recreation, as a place with links to a sense of identity, etc.).

Valuation can be assessed using different measures, such as the increase in the value of a property which has an attractive view [24] or other economic approaches; using sets of ecological or quality of life indicators to give relative values of different landscapes or elements within landscapes. Values can also be classified as [25]:

- Use value (where the landscape has a current value for some uses)
- Existence value (where knowing that a beautiful landscape exists even if a person may never visit yet it is considered worth preserving)
- Option value (where there is the possibility for many different uses which may be taken up at some time in the future)
- Bequest value (where the current generation wishes to hand on the landscape in a good condition to the next generation and forgoes a use or option value)

Sustainable Landscapes. Figure 16
A landscape in Glacier National Park in Montana where water forms a significant aspect of the attractiveness of the scene, presenting a perfect reflection of the mountain in the lake. This is one aspect of water's attractiveness (Source: Simon Bell)

The understanding and calculation of aesthetic value of landscape has been driven by two main schools over the years [26]: expert systems – measuring characteristics and qualities present in scenes, such as the presence or absence of water (see Fig. 16), and trying to be as objective in the measurements of these, relating them to some kind of scale; and perceptual systems – based on preferences of different scenes by different people (e.g., carried out by looking at photographs and rating scenes on a numerical scale). Although questions of visual landscape aesthetics are considered to be highly subjective, involving as they do matters of taste bound up with personal experience, much research has also shown that there is also a lot of similarity in which landscapes people prefer from a range of cultures. This is especially true of "natural" landscapes – mountains, lakes, and so on – though less so for settled landscapes or urban areas [2]. In some ways, the two approaches are coming together by using perceptions of value expressed by different groups to "calibrate" the more measurable or even descriptive aspects, such as key design principles [3, 18].

Cultural landscape values can also be identified using social science techniques, such as individual or group discussions, in order to uncover the extent to which certain self-identified groups associate themselves with a given landscape and what landscape elements or characteristics they mention during such discussions (see section on "Place and Place Attachment" below).

Landscape Character

Under the European Landscape Convention, only part of the approach for looking after landscape is to protect highly valued areas. The rest of the landscape – the great majority in fact, since only small areas are generally designated or protected – should also be managed. This raises the question of what exactly should be managed – certain elements? The patterns of land use? Traditional buildings? Traditional management methods? And what of the changes underway as a result of the different drivers discussed here so far? In order to be as objective as possible, the concept of landscape character has been adopted, especially by government agencies responsible for developing policies and instruments for managing landscapes under the ELC.

In the UK, for example, where this has been developed over many years, landscape character is defined as "a distinct and recognizable pattern of elements that occur consistently in a particular type of landscape" [27]. Particular combinations of geology, landform, soils, vegetation, land use, field patterns, and human settlement create character. Character makes each part of the landscape distinct and gives each its particular sense of place (see Fig. 17). In many countries, some form of inventory of the landscape has been undertaken which provides a baseline for understanding landscape change [28]. As well as topography, land use, settlement patterns, and variations in geology and ecology, the cultural landscape character is informed by historical aspects, traditional house types and location patterns, communication patterns, and specific features, such as churches, castles, unique landform, or historical events and persons.

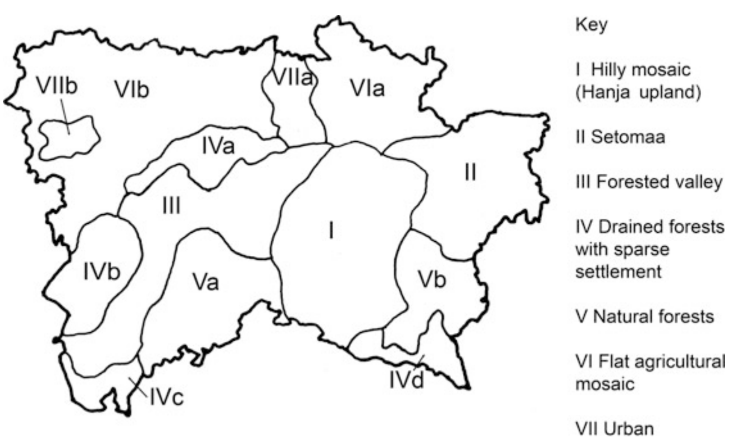
The term landscape assessment is used for the process of describing, characterizing, and evaluating landscapes. This aims to be as objective as possible in terms of the process and the description, but has to be much more than a mapping exercise. Since the definition of landscape includes the fact of perception, it is necessary to consider how the landscape appears from within – from viewpoints and from traveling through it – as well as considering other sensory aspects apart from sight, such as sound and smell. Non-physical or "soft" aspects also need to be considered, such as cultural associations. Increasingly, too, there is a need to include the perceptions of local residents and others in the assessment – at least in the valuation part – and this is anticipated in the European Landscape Convention [1].

Sustainable Landscapes. Figure 17
The character of this landscape in Tuscany is formed by the geology, the ecology, the cultivation and settlement layers. Several different kinds of landscape type can be seen within the whole scene (Source: Francisco Fellini)

The result of a landscape character assessment (LCA) is a set of maps defining different areas according to a typology (see Fig. 18) accompanied with a report describing the existing character at the time the LCA was carried out, its condition, the identifiable forces for change, and any planning policies or guidelines that may be suitable for maintaining character.

Place

People frequently identify with a particular place. If a person is asked where they live, they will name a place, not a landscape. A person will say that they are from a place, not a landscape; they may even identify themselves as being from a certain place (a Londoner, a New Yorker, or a Parisian). Thus, when involving people in landscape planning, it is best to bear in mind the fact that they think of a place not a landscape. Moreover, people do not tend to think of the physical environment as a separate entity from the social or economic environment, nor separate from the actions they take or the perceptions they hold. However, just because people tend to conflate all these things together and, in an interview or discussion, are often unable to separate them out, it does not mean that it is not important to be able to consider these aspects separately as well as together.



Sustainable Landscapes. Figure 18
An example of a county-level landscape assessment map for Võru Maakond in Estonia. The landscape character areas are fairly broad-brush at this scale (Source: Simon Bell)

Canter's Theory of Place [29] relies on the concept of "behavior settings," which are described as bounded patterns of human and non-human activity [30]. This theory has been revised and further developed into behavior settings seen as social constructs developed over time [31]. Canter was inspired by both the theory of behavior settings and phenomenology to develop his "psychology of place." In this theory, place is seen as product of physical attributes, human conceptions (perceptions), and activities. A number of studies examining people in landscapes have shown that when people talk about their lives, their perceptions, the physical environment of the place where they live, and the activities they undertake, they are not talking about separate elements but of elements bound in an interactive unit [32]. Thus, Theory of Place enables the planning field to be structured around three attributes: physical environment, activities, and perceptions, with the aim of disentangling the relationships amongst the attributes: for example, when planning deals with an attribute of the physical environment, such as major land-use changes, the interactions between activities, and perceptions with the landscape can be explored.

The meanings particular places hold for people who live in familiar surroundings, especially for a long time, are important for understanding their perceptions and activities during their lives. The places where people live often acquire special emotional significance which in turn creates attachment to that specific place (see Fig. 19). This is because people exist in particular spatial settings, and the emotional connection to a physical location is derived from the meaning given to the location through its role as a setting for experience. A range of thoughts, feelings, beliefs, attitudes, and behaviors are evoked through attachment to place [33].

The concept of place attachment is complex, multifaceted, and approached from many disciplines [34]. Place attachment also depends on interactions, beginning with the premise that all interaction is spatially located, so that place attachment occurs when a particular interaction is accompanied by significant meaning [35]. There are two interdependent components for understanding the feelings a person experiences that binds them to a specific geographic location: the interactional past and the interactional potential of the place. The first component, interactional past, refers to the past experiences or memories associated with the place. The second component, interactional potential, is the imagined or anticipated future experiences or expectations associated with the site.

Place attachment often has a special significance for older people [36]. The connection between attachment to place and the unique developmental tasks that accompany the ageing process, such as maintaining

Sustainable Landscapes. Figure 19
A village in Herefordshire in the UK set among fields. Residents may have lived there all their lives and are likely to have a strong place attachment as a result. (Source: Simon Bell)

a meaningful identity in light of age-related changes, protecting the self against deleterious adjustments due to later life, and maintaining a sense of continuity has been emphasized.

There are two dimensions of place attachment – place dependence and place identity [37, 38]. Place dependence is functional and reflects the importance of a place in providing features and conditions that support specific goals or desired activities for an individual or group. Place identity is more emotional and refers to the symbolic importance of a place as a repository for emotions and relationships that give meaning and purpose to life. Thus, place identity can be considered to be a component of self-identity [39] that enhances self-esteem [40] and increases feelings of belonging to one's community [41, 42].

Personal Construct Theory

The Theory of Place as noted above is a product of environmental psychology and itself is firmly rooted in another important psychological theory, Personal Construct Theory [43]. It is worth discussing briefly because it explains a lot of the way that people's perceptions can be understood. In this theory, people constantly take new experiences and try to organize them into an existing structure based on past experience. The past experience becomes the lens though which new experiences are processed and interpreted. People look at these experiences in terms of similarities and differences and also in terms of significance to them and to others, based on perceptions mediated by their personal constructs. Such constructs may also be shared by social groups. Thus, the data extracted from public participation activities can be evaluated in terms of how these constructs are assembled and to whom they belong. Since people make decisions based on perceptions of what they believe to be a given situation, personal or group constructs become important. A sense of national identity is an example of a personal construct held by a group as is the sense of belonging to a particular village or location. Therefore, all results from any social science research based on asking people about their lives and future intentions must be seen through the lens of Personal Construct Theory. The Theory of Place allows the organization of major factors that make up such constructs to be identified and made explicit, thus enabling the drivers of behavior or perception to be identified amongst and between groups and individuals.

Landscape and Time

So far the focus of the discussion has been on the fact that a landscape is the product of natural and human processes and experienced by people now, in the present. These processes started a long time past and continue into the future. In order to understand the way landscapes change and their degree of resilience (and therefore one aspect at least of sustainability), it is necessary to be able to consider the time depth associated with a specific landscape.

The identification of distinctive cultural landscapes can be made on the basis of the assessment of the unique combination of elements which set one area apart from another. Since landscapes are always subject to change, they express the way that natural and cultural processes interact with one another over time [9]. Thus, all landscapes are a combination of distinctive patterns which arise as a result of a range of natural and cultural processes, the balance among these over time not only producing the landscapes inherited today but continuing to affect them into the future [3]. Unlike built heritage structures, cultural landscapes can exist both as an artifact and as a system which is a product of these natural, cultural, and social processes.

The time element in any cultural landscape may vary according to several factors, such as the period at which the area was first settled and when humans started to make significant changes, thus leading to greater or lesser time depth being present in different places; the degree to which prehistoric or historical elements have survived in the landscape, perhaps as a result of the materials used in their construction or the degree to which destruction through natural catastrophes, such as earthquakes, or human catastrophes, such as wars, has taken place.

The term *palimpsest* applied to the landscape describes the results of cultural processes which have removed most of the remains of previous eras but left greater or lesser traces behind which can be seen or uncovered and which help to give an area its character and distinctiveness [44] (see Fig. 20). These remains

Sustainable Landscapes. Figure 20
The ancient Roman era theater at Selge in southern Turkey exists within a modern landscape with enormous time depth as a result of many centuries of use of this same landscape together with cultural changes yet long continuity (Source: Simon Bell)

can include physical remains, such as monuments and built structures or field boundaries and ancient trees, but also "ghost" remains, such as legal boundary lines or foundation lines of elements that no longer exist or events that happened there but left no tangible traces.

When developing a strategy to document the time depth of a cultural landscape, it is important to attempt to read it in its context of place and time [45]. Although the concept of landscape is part of the vital and imaginary experiences of a person and is an individual construction, when a community with a distinct culture with roots in the past shares the same values, the identity of a specific landscape becomes a deeper social construction [46]. The time component may therefore play a significant role in the expression of the diversity of shared cultural and natural heritage and form part of the foundation of the sense of identity of particular communities, which needs to be evaluated [47]. A multifaceted/multifunctional perspective of cultural landscapes can be a useful tool for identifying and assessing character using the local and regional historical record that is in part embedded in specific types of physical environment.

Cultural landscapes with significant time depth are frequently more than the sum of artifacts and architectural remains which have survived the long history of settlement and culture and all the changes that have occurred. However, areas with many archaeological remains may become set aside as special sites, protected as monuments and studied separately without any sense of whether the local people and communities of today have any cultural connection to them [48].

The cultural heritage of landscape can only be acquired by qualified information. Therefore, it is necessary to have tools to read the landscape, its elements and symbols, and its systems and transformations [46]. Technical approaches can be combined with classical historical–geographical methodologies for assessing cultural interfaces within the landscape [49].

In landscape, each man-made feature has its own specific, objective history (in terms of what it is, who made it, when, and for what purpose), whereas human cultures blend stories, myths, and belief with these artifacts to give them meanings which may be different from those originally intended by those who constructed them. Landscapes with a long history of development are therefore more than their physical manifestation – stories, myths, and other associations which have adhered to them over time bring something intangible but no less meaningful to the present time. Since cultural landscapes with a time depth contain so much potential meaning, it is a challenge to identify and interpret the range of aspects that may need to be conserved or managed for the future. This is where the concept of interfaces becomes useful. There are several categories of interface that may be interpreted [49]: those between past and present, between man and nature, between culture and space, and between the spiritual and the visual.

In order to understand time depth, one process that can be used is historic landscape (or land use) assessment [50]. This aims to uncover the different layers of time phases which have affected a specific area, using many different sources such as historic maps and documentary evidence. It can be seen in some ways as a refinement of the landscape character assessment methods described earlier.

Landscape as Art

A further aspect of landscapes and their sustainability is the concept that certain examples can be considered to be living works of art. This classification is attached of numerous examples of historic designed landscape parks and gardens which can be found all over the world. Many of these are associated with specific historical periods and individual designers, with different styles, with major historical persons, and also form part of broader complexes of buildings of historical and architectural merit [51].

Examples such as the palace parks at Versailles, Vaux le Vicomte, or Sceaux in France, constructed in the Baroque style to the order of King Louis XIV by the gardener André Le Notre combine all these factors [52] (see Fig. 21). However, unlike a palace which can be maintained almost indefinitely in its historical and original form with suitable conservation techniques, a landscape planted with trees and shrubs and maintained by clipping hedges grows and develops, it suffers from storms and disease and the trees eventually grow old and die. Thus, such places require periodic rejuvenation and careful management, while, at the same time, they may also be developed to reflect the needs and values of the current times.

Thus such landscapes are not only historical artifacts, but they can be considered as much works of art as the buildings, furniture, paintings, and other elements contained within the palace complex located within the park, for example. This adds a different kind of value to a landscape, albeit a relatively limited area territorially (though in some cases still a large area).

Identification and valuation of designed landscapes requires deep knowledge of the historical development of the area over time, but its continued survival depends on knowledge of many techniques of management of living elements [53].

Sustainability and Landscape

From the discussion so far it can be seen that landscape is a complex and multifaceted concept which cannot easily be identified and pinned down in a simple, single model. Since landscape is not only the physical elements which combine in a territory but include, of necessity, many aspects of human perception, the question of defining what sustainability of landscapes really means is also complicated. Since landscapes are always changing and since the very concept of landscape includes change, it becomes difficult to decide what aspects are sustainable and in what way.

From the foregoing discussion it can be seen that landscapes:

- Possess a distinctive character which can be mapped using well-developed techniques
- Are places to which people are attached and which in part at least help to form a sense of identity, but to different people in different ways and at different times
- Possess certain aesthetic qualities which affect quality of life in positive or negative ways

Sustainable Landscapes. Figure 21
The Baroque gardens at the villa of Sceaux near Paris dating from the same time as Louis XVII and also designed by André Le Nôtre. This is an example of landscape as art (Source: Simon Bell)

depending on how those qualities are manifested and experienced
- Have greater or lesser time depth leading to historical associations and values and which contribute to the aspects described above
- May form living works of art with specific historical and cultural associations

Therefore it is necessary to consider each of these facets as being sensitive to change depending on the nature, rate, type, extent, and the degree of reversibility of change. It is possible to consider three main objectives of landscape management in the context of landscape change pressures:

- Conservation and protection of existing character and values
- Improvement or restoration of the landscape where it may be unattractive, decaying, disturbed, or lacks identity
- Changing the landscape where it is derelict, abandoned, destroyed, or dysfunctional

The aim, taking the lead from the aims of sustainable development from the Brundtland Commission [54], is to retain or enhance the values and functions of a given landscape so that it satisfies the requirements of current generations while safeguarding the options for future generations. In managing change, it is therefore necessary to understand the sensitivities of both physical landscape and people and the capacity of both to cope with potential changes of different types according to the pressures being exerted. In order to do this, it is necessary to understand what makes landscapes and people sensitive to landscape change and how to measure it.

The DPSIR approach (Drivers-Pressures-State-Impact-Response) [55] is commonly used to try to understand how change occurs, and a series of related indicators show the effect of those changes. Applied to landscape, therefore, it is necessary to consider each element of the DPSIR system:

- Drivers: the main drivers of landscape change are demographic change, technological developments, economic cycles, cultural shifts, planning policies, and environmental change. Each of these can be modeled to a certain extent (with greater or lesser degrees of confidence) and can be applied, depending on the models, at different territorial scales. These drivers affect different regions in different ways through the pressures they exert.
- Pressures: the drivers exert pressures on the landscape such as urbanization, spread of urban sprawl, abandonment of remote areas, increased need for transport infrastructure, pollution, change in agricultural techniques, changes in demand for commercial or business land, and construction of technical elements. Such pressures have greater or lesser impacts. People may feel threatened by some or all of these pressures. The pressures change the state of the landscape.
- State: the resulting change in state from that existing before the pressure was applied can be measured and presented using an indicator. Changes in the physical state of the landscape may result in changes to landscape character which may reduce it, strengthen it, or change it (for the better or worse depending on how it is viewed). A particular place may change as a result of urbanization and by an influx of people from elsewhere so that the attachment to that place by the original residents may be weakened, and with it their sense of identity. A cultural landscape which relies on traditional management practices may be lost if modern intensive agriculture takes over or if the area becomes depopulated.
- Impacts: these occur as effects on the landscape and on people. The impact may increase or reduce the attractiveness of a place to live, increase or reduce quality of life, increase or reduce the integrity of a cultural landscape that has survived many centuries. Such impacts need a set of indicators and the calculation of thresholds, so that the degree of impact and the way it affects the sustainability of the landscape can be assessed and remedial measures taken as necessary as part of a planned response.
- Response: the government, government agencies, local authorities, NGOs, or citizen groups and landowners may each seek to control, avoid, prevent, or mitigate the impact by planning or other means and there need to be tools to do so: legal, regulatory, or compensatory, for example, so that any negative effects can be reduced to an acceptable level. Impact assessment undertaken before pressures to develop become actions on the ground is needed, as already exist in many countries (although the mechanisms are currently weak in assessing landscape impact in many places).

Landscape Sensitivity

An important first step in understanding how an expected pressure for development is likely to affect the sustainability of a landscape is to assess its sensitivity. This can be divided into the effect on landscape character, on historical integrity, and on landscape value. Methods of assessing this have been developed for landscape and visual impact assessment as part of the general environmental impact assessment methodology [56].

The potential effect on landscape character depends on the strength and integrity of the landscape likely to be affected by development pressures as well as the scale and nature of the development, and any specific qualities in the landscape which contribute to character and which may be altered. By way of illustrating the potential effect, an example of a development which may be controversial in this respect will be illustrated. Renewable energy is frequently cited as a sustainable technology. Wind turbine developments have to be located in areas where there is plenty of wind, and in the UK, as in many areas of the world, the best sites to be found in hilly or mountainous regions. These often have a strong and wild character into which the presence of large technical elements such as turbines as well as access roads and tracks, power lines, and other features may be considered intrusive and out of place. If the landscape is of relatively small scale, the turbines may appear to dominate it; and if there are many of them, the extent of the landscape affected may be significant (see Fig. 22). Thus, while the sustainability of the renewable energy development may be positive in one regard (energy), it may be considered unsustainable in another regard (landscape). Thus, planning at a strategic level to direct such developments into landscapes with characters which offer greater capacity are likely to help to secure a more sustainable landscape [57].

Effects on historical integrity of a landscape as a result of development pressures will also depend on the nature and scale of the development and the specific historical layers involved. If the landscape can be described as an “archaeological landscape” or one where a complex of remains from specific periods is clearly a dominating factor in its character, then similar effects would apply as for landscape character described above [50]. While, as noted frequently in this paper, the landscape is always changing, current concerns about change also demand that landscape conservation is practiced wherever appropriate. This is implicit in the ELC [1]. As noted in the introduction, there are several main drivers of change, any or all of which may have an effect on the historical integrity of the landscape. One key change is intensification of agriculture, which may

Sustainable Landscapes. Figure 22
An example of a windfarm located on a fairly wild moorland in the south of Scotland. Not everyone may think such a development fits into such a landscape (Source: Simon Bell)

not only remove important ecological elements but also remains which have considerable time depth [4]. These may be field patterns, hedgerows, and old trees, for example. Time depth may also be manifested in strong continuity of cultural traditions such as vernacular buildings in farms and villages which may be replaced by standardized elements which break the sense of time continuity.

The effect on landscape value may be easier to assess because many landscapes have been designated and protected in some way as a result of generally accepted evaluation as a special landscape. In most countries, there are categories of protection of landscapes for scenic reasons (or scenery combined with historical and ecological values). These often have specific legal protection of various degrees of strength. The national parks in the USA were designated for a combination of scenery and public access [58] (see Fig. 23) and are owned by the Federal Government, so that development within them is strictly controlled. However, in many places, development just outside and visible from within is not controlled and leads to negative effects on the landscape. Since the US parks are mainly natural, "unspoilt" landscapes, they have specific qualities which would be vulnerable to many forms of development, although their sheer scale and extent protects them since the effect of peripheral development usually does not penetrate into the core areas. European national parks, such as those found in the UK, are usually cultural landscapes and in part rely for their value as much on cultural elements and ongoing landscape management as they do on their natural scenery [59] (see Fig. 24). In such circumstances, development pressures exists – not least for tourism and recreational infrastructure – but stronger planning controls usually apply and can be used to limit the rate and scale of impact of change. Many people would argue that limited development in this way is necessary to ensure that these landscapes are sustainable in the sense of enabling traditional management practices that led to the character and value of the landscape developing to continue means that they need economic support.

Sustainable Landscapes. Figure 23
Yosemite National Park in California is protected and also highly valued for its spectacular qualities and for the spiritual benefits many people obtain here. It is primarily a natural area, not significantly affected by human activity, although not wholly devoid of it (Source: Simon Bell)

Visual Sensitivity

Since the definition of landscape includes the phase "as perceived by people" [1], any evaluation of sustainability must include the potential negative or positive effects of development pressures on the people who are experiencing the landscape. In the guidance on landscape and visual impact assessment [56], methods of assessing visual sensitivity are described. These generally consider three (sometimes four) factors: the visibility of the likely or proposed development, the numbers of people seeing it and likely to be affected, and the nature of the viewing experience (the fourth factor may be the value of the landscape). Each of these has to be set in the context of the way the development may be viewed.

Using the example of the wind turbine development used earlier, the visibility means the extent over which the development may be visible, radiating out from the site to a distance beyond which it ceases to be visible to the human eye (around 35km) [56]. The visibility may be affected by many factors – intervening hills, vegetation, or structures which may screen the development or parts of it from view. The numbers of people likely to see the development will vary from place to place – in some locations, the population of a whole city may be able to see the development while in others a handful of people may be present in a particular part of the landscape. The visibility from key viewpoints may be modeled using photomontages, for example, as shown in Fig. 25.

Sustainable Landscapes. Figure 24
The English Lake District National Park combines natural geology and mountainous scenery with human activity cultivation and traditional features (Source: Simon Bell)

Sustainable Landscapes. Figure 25
A photomontage of a windfarm development showing extremely accurately, how it would appear from a specific viewpoint (Source: Margaret McKeen)

The nature of the viewing experience depends on the frequency and the reason for seeing the development. Tourists may be visiting an area in order to obtain a certain type of viewing experience which may not include turbines in their list of desirable features. Long-term residents may be affected by the change to the scene while commuters driving to and fro along a road may not focus on a distant development even though there are large numbers of them visible along a specific route, for example. The context in which the development is seen – the landscape setting, the distance, the relative scale, the lighting conditions, and the character will also have an effect. If the development is seen with a backdrop of wild mountains, it may not be seen as favorably as if the landscape already contains many other technical elements. The calculation of sensitivity may be a technical exercise based on the factors described above, but this takes no account of how people perceive turbines and whether they see them as negative or positive features in a scene [56]. Turbines may symbolize sustainable development and be seen by some people as positive elements providing evidence of action to protect the environment in general and in the long term, while others may see them more negatively as spoiling the landscape.

Taking the effect of such preferences and perceptions into account in sustainable landscape planning is no easy task because there are many potential stakeholders involved who operate at different spatial scales – local people, regional considerations, national priorities, and so on.

Landscape and Visual Capacity

One approach to strategic sustainable planning of landscape development is the concept of landscape capacity. This means the inherent capability of a given landscape to accept or absorb change without detriment to its character or quality [57]. In some ways, this can be seen as the converse of sensitivity – the higher the sensitivity the lower the capacity, and vice versa. It is not quite that simple because there are factors related to the landscape pattern and structure which may increase or decrease capacity, depending on how they are taken into account. In the example of wind turbines, capacity may depend on aspects, such as landscape scale, the location and position of the development, the number of turbines proposed, and the cumulative effect of several developments in the same landscape.

Visual capacity can be considered in the same way – the visual extent in the scene, the cumulative impact of seeing several separate developments at once, or when traveling along a road for example, as well as the effect of a development (such as of wind turbines) in the background of a scene as opposed to the foreground [57].

In both cases noted above, it is difficult to say whether any landscape which has no examples of a specific development – such as a wind turbine – has any inherent capacity, since such objects are entirely new and alien to the scene. Thus the first step is to introduce the first one, which thus involves a change of state from a landscape with no turbines to one with turbines. After the change of state has occurred, it is more appropriate to consider how many and what configuration of turbines (or any other development) can be added until a tipping point is reached. When the visual impact is considered, this may be different for different people and cannot be calculated by some form of objective expert system, although many authorities would probably like it to be so.

The question of what is a sustainable capacity in a given landscape is therefore a difficult aspect to answer as it is not possible to apply decision rules to something which depends on many qualitative factors which have to be judged on site or modeled (see section on "Tools for Evaluating Sustainable Landscapes" below).

Monitoring Landscape Change

At the heart of attempting to define and manage a sustainable landscape has to be some kind of process for monitoring the landscape and its change over time. Many examples of monitoring change exist which are based on measuring something which can be mapped [28]. This is useful for some aspects of landscape as it is defined here – changes in vegetation, field boundaries, settlement patterns, or construction of various elements will have an effect on character, for example, although trying to measure this by assessing changes in area of vegetation may not be so directly correlated because plan area may very well not equate with visual area. Since the perceptual aspect of landscape is so important, this must also be taken into account in any monitoring process and qualitatively assessed.

One approach is to use a sampling system. In many landscape (ecological) monitoring systems, such as the UK countryside change program [28], a set of sample areas are visited and their component vegetation and other elements measured and evaluated using a set of criteria. For the landscape, a set of sample viewpoints can fulfill the same function, using panoramic photographs taken at suitable time intervals (the same as for the vegetation or other monitoring) and when linked to mapped information (for which the visible part of the landscape can be identified), the qualitative aspects of the changes can be addressed [60].

Indicators of Sustainable Landscape

According to the DPSIR approach and any method of assessing the effects of change as detected through a combination of map- or photo-based systems, there need to be indicators which show the direction and degree of change in some meaningful way and help to identify when threshold values are approached. Given the subjectivity attached to landscape and the way people may react to change, as well as the perceptual nature of landscape, selection of suitable indicators is by no means an easy task. One attempt has been developed which synthesizes a number of approaches concerning the evaluation of the visual landscape character [61]. This uses nine concepts, and for each concept identifies several dimensions, attributes, and potential indicators. Table 1 summarizes these. The indicators are, in the DPSIR terminology, State indicators, and over time, changes in state could be assessed by them (Fig. 26).

Tools for Evaluating Sustainable Landscapes

There are various technological solutions for evaluating the sustainability of a landscape. These include visualization tools and analytical tools.

Visualization tools range from simple sketches of what a landscape is expected to look like given a certain level of development or the inclusion of certain elements in the landscape, through increasingly sophisticated computer-based or digital graphics which give more realistic or quasi-realistic impression of the appearance of the landscape, to virtual tools which allow the landscape to be modeled in three dimensions and then for the potentially affected population to experience moving around the landscape testing the full impact of where the development can be seen (and heard) [62]. Increasingly, visualizations constructed to specific standards, in order to replicate as closely as possible the viewing experience, have to be provided in support of the assessment of landscape and visual impact. However, static photomontages taken from selected viewpoints are not as helpful as the virtual environment where the potentially affected person has the chance to explore their neighborhood freely and to come to their own conclusions (see Fig. 27), as opposed to the preparation of a technical exercise by professional experts as is the case at present.

Analytical tools include geographic information systems (GIS) used to evaluate, using a system of metrics, the effects of different landscape options or change scenarios and how people respond to them [63]. Such systems can model the visibility of a given landscape from the point of view of the screening effects of landform so that the exact proportion of the landscape likely to be affected is calculated. Metrics need not be only associated with the visual effects but also with habitat effects, drainage, amount of sealed surface, or accessibility from residential areas – aspects which have a wider effect on sustainability than the visual/experiential and which may affect the suitability of a plan or design in the wider context of the term.

Quality of Life and Landscape Change

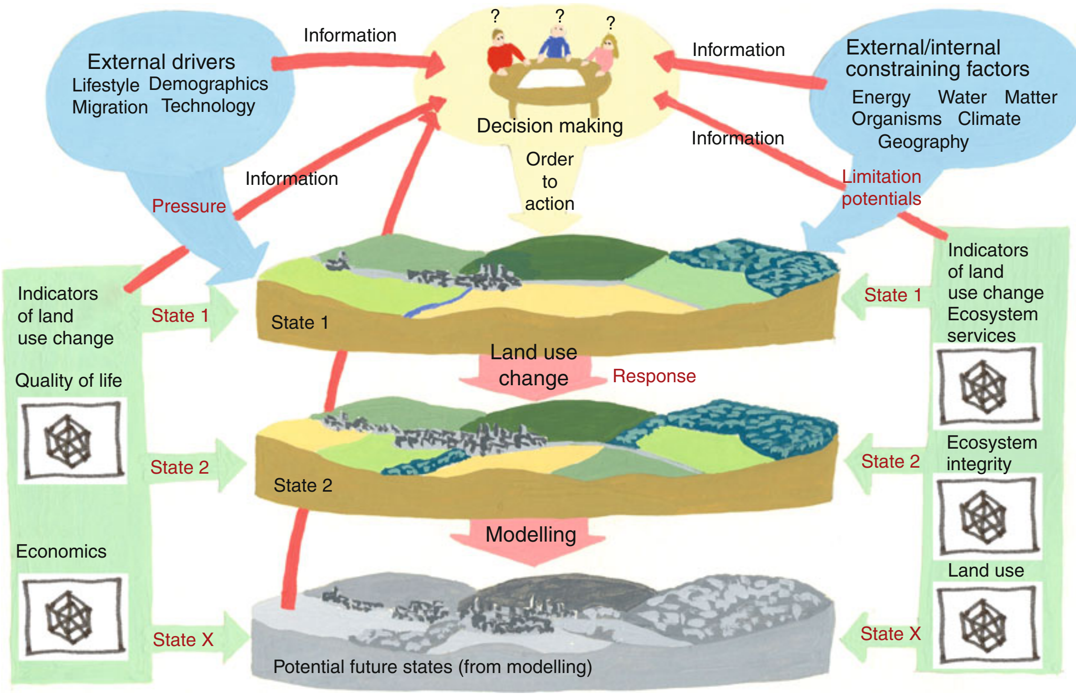
In part, at least, the quality of the landscape affects the quality of life of people living in it or experiencing it. This was realized many years ago by the leading author Nan Fairbrother in her book "New Lives, New Landscapes" where she attempted to define how new urban areas could be designed to increase the quality of life of residents who could move from slum environments in the UK to better housing in a series of new towns [64].

More recently, the concept of quality of life has become popular in many of the large indicator sets for measuring things like sustainable cities, for example [65]. Many of the indicators have nothing to do with landscape – such as the number of teenage pregnancies or adult literacy levels, but some do – such as accessibility of green areas or air quality, for example. These indicators are often measured very crudely and certainly do not take into account the fact that the sensitivity of people may vary for all kinds of reasons. For example, some people prefer to live in city centers where the environment may not be green and where crime levels may be high, but where the life is vibrant and where there is a lot of social and economic activity (see Fig. 28). Young professional adults may be part of this group. Families with young children, however, may prefer suburbs with clean air, lots of green places, and high degrees of safety and security. Yet others may prefer to live in rural areas and are willing to spend long periods commuting into the urban areas for work. Such people belong to different lifestyle groups or, in marketing jargon, "tribes" [66].

As the landscape changes, as the result of various drivers and pressures, the quality of the landscape measured in terms of the indicators noted above, as well as factors such as availability of green space, air quality, noise pollution, safety and security, or convenience of public transport, may lead to a lowering of the perceived quality of life. If people can afford to move house, then the threshold point at which landscape

Sustainable Landscapes. Table 1 Indicators of quality of visual landscape character (Source: [7])

Concept	Dimension	Attribute	Potential indicator
Stewardship	Sense of order, sense of care	Signs of use or abandonment, vegetation succession, condition of elements	Percentage of abandoned land and stage of succession
			Condition of buildings; Areas under positive management
			Length and condition of hedges and walls
			Presence of waste or debris
Coherence	Presence of harmony, unity	Land use, water, pattern	Percentage of land use in natural condition
			Presence and pattern of water
			Repeatability of patterns, colors, textures
Disturbance	Lack of contextual fit, lack of coherence	Disturbed land and disrupted natural areas; construction, infrastructure	Number of disturbing elements
			Percentage area impacted by disturbance
			Visibility of disturbing elements
Historicity	Historical continuity, historical richness	Visible time layers, cultural elements, traditional agricultural patterns and practices	Presence of cultural elements
			Shape and type of linear historical elements
			Age of historical elements
			Number of time layers
			Presence of traditional land use and pattern
Visual scale	Visibility, openness, grain size	Topography, vegetation man-made structures	Viewshed size; Viewshed form
			Depth of view, degree of openness, grain size
Imagebility	Spirit of place/ genius loci, uniqueness, distinctiveness	Spectacular elements, iconic elements, panoramas	Viewpoints
			Presence of spectacular, unique or iconic elements and landmarks
			Presence of water bodies, percentage area of moving water
Complexity	Diversity; variation; complexity of patterns and shapes	Point and linear features, land cover, land form	Number of objects and types
			Evenness index, dominance index
			Diversity indices; Shape diversity
			Size variation indices
			Heterogeneity indices
Naturalness	Intactness, robustness, natural vegetation, lack of human influence	Natural features; structural integrity of vegetation; vegetation/ land-cover type; water; management; patch shape; edge shape	Fractal dimension; vegetation intactness; percentage area with permanent vegetation cover; lack of management; management intensity (type and frequency), naturalism index; degree of wilderness
Ephemera	Seasonal and weather-related changes	Land cover/vegetation; animals; land use (plowing, etc.); water (color reflections and waves); weather	Percentage of land cover with seasonal change
			Presence of animals
			Presence of cyclical farming activities; Percentage area water
			Projected and reflected images; Presence of weather characteristics



Sustainable Landscapes. Figure 26
A sketch showing how indicators can be used to evaluate differences from one landscape state to another and also to model future potential states. It relates to the DPSIR model (Source: Simon Bell)

Sustainable Landscapes. Figure 27
The Virtual Landscape Theater can be used to simulate the changes to a landscape as experienced by people within the landscape and moving around it (Source: Simon Bell)

Sustainable Landscapes. Figure 28
The centre of Manhattan, New York City, may be attractive as a place to live for some people but not for others. Different people belonging to different “tribes” have different views as to whether such a place is suitable for their lifestyle (Source: Simon Bell)

change triggers widespread movement of residents acts as a signal that the landscape is no longer sustainable. Monitoring changes and modeling potential futures as a result of applying the drivers of change can be linked with the way different people are likely to react to different combinations of change and thus to points where quality of life is likely to drop significantly.

Sustainable Landscape Planning, Design, Construction, and Management

The origins of sustainable planning and design can be found in Ian McHarg's seminal work "Design with nature," which advocated looking at many different factors ranging from geology and hydrology to soil and natural vegetation when planning where to locate development, for example [67]. This approach was a pioneer of "sieve mapping" as a tool for evaluating and analyzing the interaction between different layers of information, a task which had to be done manually using overlays at the time (the 1970s), but which is now done using GIS with much more sophistication. The scale at which McHarg worked was mainly at a regional scale, but the methods are also applicable at smaller scales. More recently, the idea of understanding nature, culture, and natural and cultural processes has been developed with an advanced understanding of how these operate, so that the concept of designing with natural and cultural patterns and processes has taken a step forward [3]. One specific area where there have been contentious issues of landscape planning, design, management, and sustainability has been in forests – seen as a renewable resource for many values, but when exploited for timber to the exclusion of everything else has major impacts on ecological, aesthetic, social, and recreational values. Specific methods have been developed to incorporate sustainable design into forestry planning, design, and management [68] (see Fig. 29).

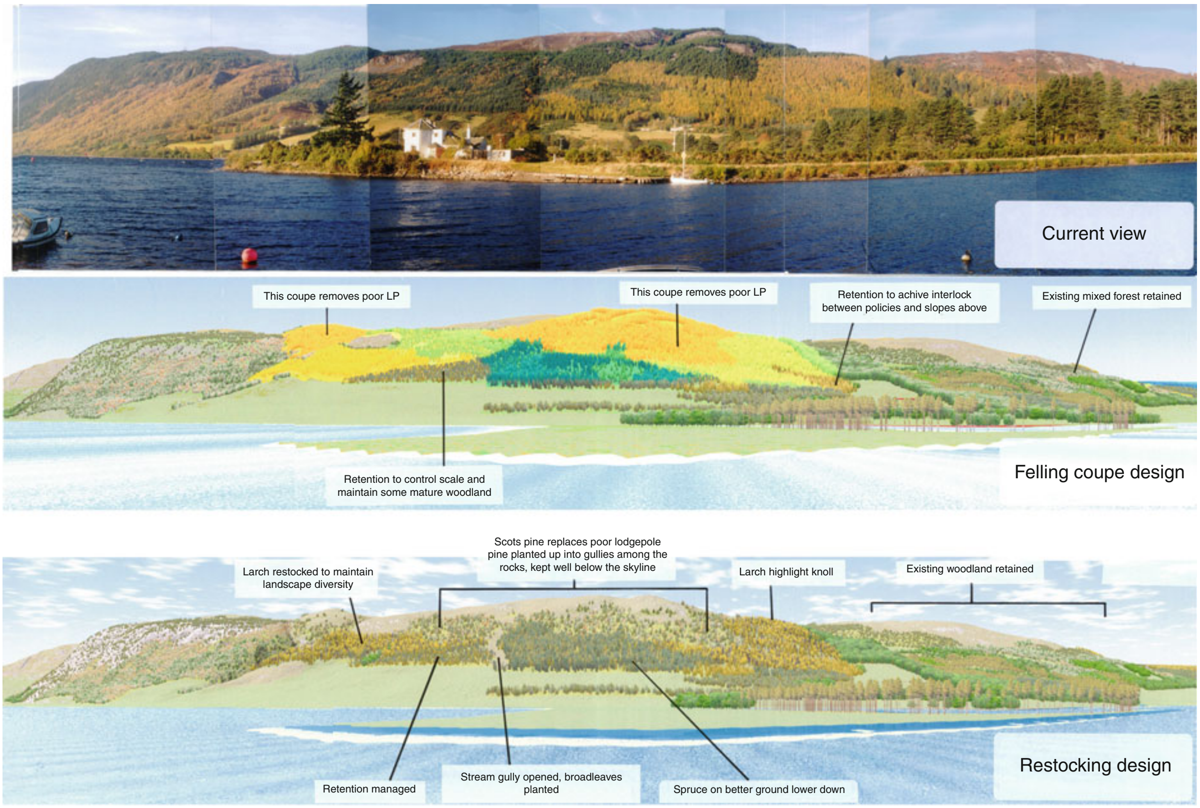
While most of the foregoing has considered the subject of landscape at a fairly large scale and often in the context of landscape planning, at the scale of the design project, sustainability also has to be taken into account. The kind of landscape projects which fall under this category include public parks and green spaces, housing areas, recreation sites (such as in forests or national parks), infrastructure projects, forest landscape design, or restoration of historic parks and gardens.

Aspects to include in sustainable design are concerned with both the process used to develop and create a landscape project, and the elements that comprise the project and its management and maintenance (see Fig. 30). Process aspects may include the role of stakeholders in the preparation of the design brief and objectives, consultation or participation of local people in the development of the design, the contribution of the construction and maintenance, as well as the presence of the landscape project to the local economy and the way in which the project takes account of ecological and other environmental issues.

Normally a landscape project of whatever scale sits within a wider environmental, social, and economic context, and so should be evaluated as to how it contributes positively to these over time. Since landscape projects develop and mature over time (a new park is not a finished project but is the start of a process of growth and development which may take decades to mature), their sustainability needs to be considered over the appropriate time frame. The continued involvement of local residents in the way the landscape is managed and possibly modified over time so as to keep contributing the right mix of benefits as the community changes is one aspect; the availability of adequate economic resources to manage the landscape over time so that the investment is not wasted and so that the values continue to flow is another; the maintenance of ecological benefits through the management of the vegetation and habitat elements is also necessary. In places which attract many users, such as outdoor recreation areas within protected landscapes, there may be conflicts with increasing demand from users placing pressure on the natural and financial resources and risking a loss of sustainability [69].

Some landscape projects do not require special funding but are implemented and managed through other means such as in the case of a forest landscape where the activities of forest management, timber harvest, and afforestation are the means by which the design is implemented. In such cases, continual revision and the use of approaches such as "adaptive management" can be applied to ensure continuing sustainability [70].

For those projects where construction and management is undertaken by special contracts – such as the development of a new urban park or a housing



Sustainable Landscapes. Figure 29
An example of large-scale design of a forest in the Highlands of Scotland to show how it will appear in the landscape after certain improvements have been made (for greater sustainability) (Source: Steve Conolly)

Sustainable Landscapes. Figure 30
New urban housing in the old docks at Malmö, Sweden, designed to be sustainable in design, construction, use of materials and energy and circulation of water (Source: Simon Bell)

area – the use of resources in the construction has to be considered. This includes the use of renewable materials, the use of locally sourced materials, the need for importing topsoil, the need for irrigation and water management for planting areas, the use of local labor in construction, and the life-cycle analysis of materials. At maintenance and management, the use of energy, irrigation, pesticides, machinery, and the longevity of materials should all be considered [71].

Future Directions

As noted in the introduction, landscape in the sense used here – and area of land as perceived by people – the many disciplines interested in this, from landscape architects to environmental psychologists, cultural geographers, or philosophers are constantly exploring new or modified ways of looking at and considering landscape. With the advent of the European Landscape Convention, in Europe at least, the issue will have greater importance and require considerable research from a range of disciplines in order to see its successful implementation. The inspiration of the convention may also have an effect in other regions of the world.

It is also likely that, as the importance of the landscape and outdoor environment increases in terms of its value for human health and well-being, for example, more pressure will be placed on urban green areas and landscapes close to where people live. The evidence base for many of the benefits is not as scientifically rigorous as it might be so this is one area where scientific work is likely to develop [72]. Relating such issues to scales of quality of life which reflect the actual perceptions and values of different societal groups offers further means of linking specific well-being aspects to places and people in a much more sophisticated way.

One major area which has an impact on landscape is the current planning trend to try to make cities more compact in order to reduce the amount of land taken into the urban area and the development of sprawl [73]. While sprawl is a major problem, caused by low-density development on the urban edge associated with transport corridors and ex-urban industry or commerce, there may be negative effects of too much compactness when green space within the urban envelope tends to be squeezed out. Given the importance of green areas within the urban landscape for quality of life and ecosystem services, there is a need to try to ensure that solving one problem does not cause another. This issue is likely to continue as a major one since urban areas are continuing to grow and controls on either sprawl or maintenance of green space are weak in many countries.

Another area where there are likely to be increasing tensions surrounding sustainability is in the effect of sustainable development technologies on the landscape. The example of wind turbine development has been used earlier. While many people advocate the use of renewable energy, other people do not like it to be developed in visually attractive or "natural" landscapes, such as in hilly or mountainous country. Thus, there are two aspects of sustainability in tension with one another. As such developments increasingly affect landscape capacity thresholds, the tensions are only likely to increase.

Participation in planning of the landscape is one important aspect of some approaches to sustainable landscapes and is likely to become more important. This can be tied in with the environmental movement and the various pressures to reduce resource use and to localize more aspects of products and services yielded by the landscape. It also includes the greater involvement of people from different communities in decisions about the development or protection of local landscapes, especially where they may be many competing demands and perceptions about a place and different degrees of place attachment. A number of tools for public participation exist, but the use of newer technology such as virtual tools, which allow local people to experience different potential landscape futures and to use this for exploring their views and perceptions, is likely to help in resolving such disputes.

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Urban Forest Function, Design and Management

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Article Outline

Glossary

Green infrastructure Green infrastructure is a planned network of multifunctional green spaces and interconnecting links which is designed, developed and managed to meet the environmental, social, and economic needs of communities.

Urban forest The sum of all woodland and other tree-based vegetation in and immediately surrounding an urban area.

Urban forestry The art, science, and technology of managing trees and forest resources in and around urban communities for the environmental, social, economic, and esthetic benefits trees provide to people.

Urban green space All vegetated lands in urban areas, including parks, woodland, gardens, cemeteries, orchards, etc. Often urban green space is used in terms of publicly owned green space.

Urban greening The planning and management of all urban vegetation to create or add values to the local community in an urban area.

Urban woodland Forested land located in or close to urban agglomerations, with a multiple forest functions approach. Typically, social and environmental forest services are the focus of urban woodland management.

Definition of the Subject with Brief Historical Background

Land use planners have increasingly been focusing on urban green infrastructure rather than individual green elements. Moreover, politicians, researchers, and practitioners have had to deal with the contributions of this urban green infrastructure to the quality of urban life and environment. They have started to realize that more integrated green area planning and management are required to meet current societal demands when operating in high-pressure environments. This has led to the emergence of new concepts and approaches of a more integrative kind. Urban greening, for example, has developed as the planning and management of all urban vegetation to create or add values to the local community in an urban area [40, 66]. Another more integrative concept resulting from the above-mentioned developments is that of urban forestry.

Urban forestry has become defined as the art, science, and technology of managing trees and forest resources in and around urban communities for the environmental, social, economic, and esthetic benefits trees provide to people (developed from [27, 50]). In its broadest sense, urban forestry embraces a multi-managerial system that includes municipal watersheds, wildlife habitats, outdoor recreation opportunities, landscape design, recycling of municipal wastes, tree care in general, and the production of wood fiber as a raw material. Urban forestry includes activities carried out in the city center, suburban areas, and the peri-urban or interface area with rural lands.

Growing awareness about the need for more integrated approaches to urban green planning and management, and specific threats to urban tree populations caused by pests and diseases (such as Dutch Elm Disease) led to the emergence of urban forestry in North America during the 1960s. Europe and other parts of the world followed with, for example, international

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research networking intensifying during the late 1990s (e.g., [35, 39, 50]). In spite of this, urban forestry is an emerging and still developing field. Differences can be noted in the definition and implementation of the urban forestry concept in different parts of the world, with, for example, a traditional focus on urban woodland in Europe (e.g., [40]). However, the concept of urban forestry as encompassing the planning, design, establishment, and management of trees and forest stands with amenity values situated in or near urban areas, has become more widely accepted.

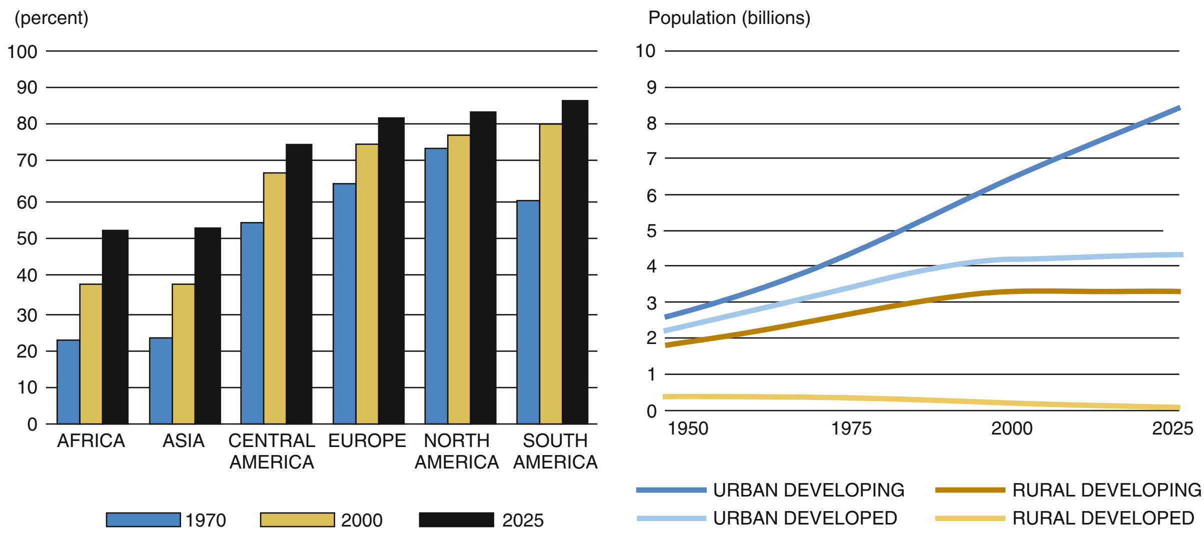
In Europe, the definition of urban forestry has been adapted into the Urban Forestry Matrix see (Fig. 1).

The matrix shows the integrative scope of urban forestry, incorporating urban and peri-urban tree resources, including single trees and groups of trees along streets, in public and private parks and gardens, cemeteries, and so forth. The distinction between the three types of locations included in the matrix arises from three different levels of planning and management hierarchy, stress, establishment techniques, average life times, and costs in relation to establishment and management [55]. Street trees, for example, are usually single trees with a low average lifetime due to a high stress level. Moreover, street trees generally involve the highest management costs. Park trees are also to be found individually or in small groups, with a medium or high average lifetime, medium stress level, and medium costs for establishment and management. Urban woodland trees are usually established in stands by means of seeding or planting of small trees, with a high average lifetime, low establishment cost, and, relatively, low management costs.

The matrix also shows the different relationships and interactions between human society and urban forest resources. At the more strategic level, form and function of urban forests provide a basis for policy-making, planning, and design. The selection of plants for the urban environment, and tree establishment involve technical activities. Management, finally, is aimed at bringing strategies and technical operations together in order to maintain and develop sustainable and multifunctional urban forest resources.

	Street trees	Trees in parks, private yards, cemeteries	Urban woodlands
Form, functions, design, policies and planning			
Selection, establishment and other technical approaches			
Management			

Urban Forest Function, Design and Management. Figure 1
The Urban Forestry Matrix (Based on [37], photos by Kjell Nilsson)



Urban Forest Function, Design and Management. Figure 2
Estimated urban population by region (From [87])

As visualized in the matrix, urban forestry is an integrative approach, combining street and garden trees with urban woodland, and extending from policy-making to establishment, maintenance, and management activities. Integration has been described as one of the key characteristics (and strengths) of urban forestry [35]. Other characteristics include its strategic scope, its social inclusiveness (emphasizing stakeholder involvement), its focus on multifunctionality of the urban forest resource, and its embracing of the urban settings and dynamics in which urban forests are situated.

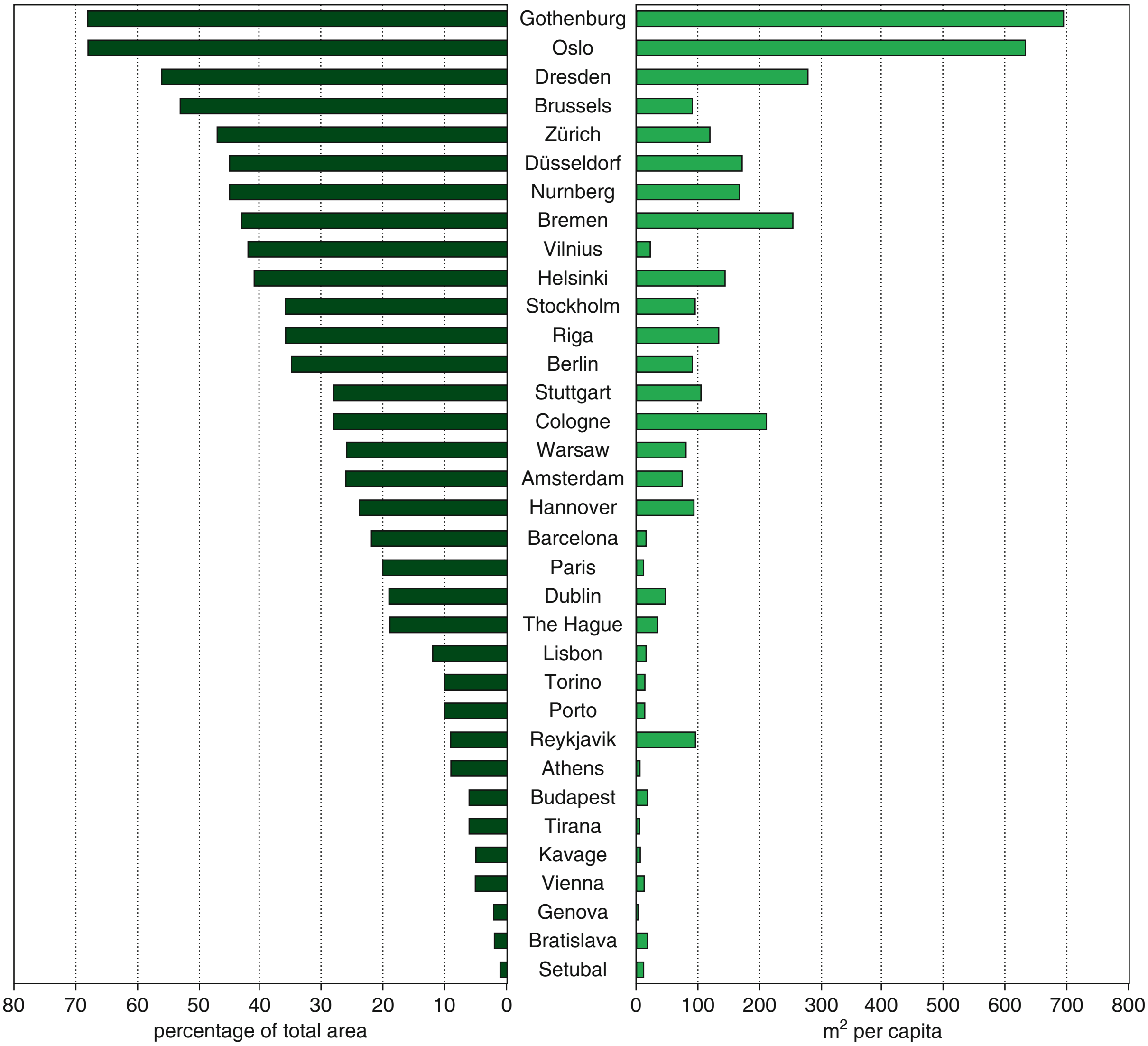
Introduction: Urban Forest Resources in a Global Context

In 2008, for the first time in human history, the number of people living in urban areas exceeded the rural population. Urban areas in developing countries will account for nearly 90% of the projected world population increase of 2,700 million people between 1995 and 2030.

Urbanization is a worldwide phenomenon; the World Resources Institute [87] estimated that in 2025, more than 50% of the African and Asian populations would be living in urban areas. In Central and South America these figures will be between 75% and 85% (Fig. 2).

Managing urban population change will be one of the most important challenges during the next decades, along with moderating the impacts of climate change. In developed countries, the urban future will involve dealing with complex changes in the composition of urban populations and containing urban sprawl beyond the suburbs to retain the critical ecosystem services that will sustain population growth. In developing countries, where 80% of the world's population resides, central issues will be how to cope with an unprecedented increase in the number of people living in urban areas and with the growing concentration of these urbanites in large cities with millions of residents and declining availability of natural resources.

Throughout Europe, the proportion of urban green areas varies considerably, from less than 5% in cities like Tirana and Bratislava to nearly 70% of the area of Oslo and Gothenburg [11] (Fig. 3). In comparison, the figure for Mexico City is only 2.2%; in relation to the number of inhabitants, this only provides 1.94 m^2 per inhabitant, which is far below the 9 m^2 recommended by the World Health Organization [6]. However, these figures should be taken cautiously since definitions of green space and city boundaries differ a lot between cities. A suggested measure of urban environmental quality is the location of green areas within a walking distance of 15 min or less from all housing areas.



Urban Forest Function, Design and Management. Figure 3
Green areas in selected European cities [11]

This criterion is met for the citizens in, for example, Brussels, Copenhagen, Glasgow, Madrid, Milan, and Paris and, in general, for more than 50% of the population in most European cities [78].

The Benefits of Urban Greening

The green infrastructure of cities provides urban society with an essential range of goods and services, representing the three dimensions of sustainable development: Environmental, economic, and social sustainability.

Environmental and Ecological Functions

Reduce Air Pollution Trees intercept particulate matter and absorb such gaseous pollutants as ozone, sulfur dioxide, and nitrogen dioxide, thus removing them from the atmosphere. Several studies conducted in the USA as well as in Germany and China have shown that urban tree cover has the potential for improving air quality [7, 57, 88]. Protective plantations along heavily trafficked roads and around industrial areas are, therefore, an effective means of reducing air pollution. In Santiago de Chile, urban forests were found to be a cost-effective air quality improvement policy [15]. But this should obviously not be taken as an excuse for neglecting to combat pollution at its source.

Even though plants absorb carbon dioxide and produce oxygen, it is still important not to assign plants excessive significance to the urban environment. Harris [26] reminds that plants really have only a minor effect on the carbon dioxide and oxygen content of urban air. Photosynthesis in the oceans accounts for between 70% and 90% of the world's total oxygen production, for which reason it is absolutely vital that they be protected against pollution. Even a minor reduction in the oxygen content of the air will cause a large percentage increase in its carbon dioxide content, which would reinforce the greenhouse effect, thus leading to a rise in the global temperature. Harris [26] also stresses that urban vegetation has an especially beneficial effect on air pollution through its ability to cool urban heat lands and reduce the quantity of airborne particles.

Protect Water Resources and Reduce Stormwater Runoff Before modern urban areas made their appearance, rainwater was handled locally. It ran in stone fascines in the ground or out onto fields and pastures. The towns also had streams and wetlands that functioned as recipients. The great change came after the Second World War, when serious attempts were made to drain the water away from residential areas, streets, and squares in underground sewer pipes. Thus, the traditional water cycle of the towns lost its main source. Instead, costly drinking water is now used for watering greens and plantations.

When it falls on roofs and paved areas, rain has become an environmental problem, instead of being a resource that appeals to the senses and benefits plants and animals. Run-off from roads, streets, parking areas, and even some roofs is polluted. Thus, draining rainwater into sewers means that these pollutants end in watercourses, lakes, and the sea. On the other hand, rainwater that has filtered through the soil is considerably cleaner than the water from purification plants [30].

Protection of riparian woodland can be of particular importance for surface water quality. The hydrological function of urban woodland and trees is increasingly stressed as protection of drinking water resources. For example, in Denmark, new woodland areas established close to cities consider this function as a primary one next to recreational benefits [29].

Reduce Harmful Influence of Sun, Wind, and Temperature By transpiring water and shading surfaces, trees lower local air temperatures. Because trees lower air temperatures, shade buildings in the summer, and block winter winds, they can reduce the consumption of building energy and consequently reduce the emission of pollutants from power-generating facilities [48].

Temperatures will change in the future and the so-called urban heat island effect will strengthen the effects of climate change. Results from the ASCCUE (Adaptation Strategies to Climate Change in the Urban Environment) project show that green areas can play an important role for smoothing the effects of rising temperatures. The results show that for the city of Manchester increasing green cover by 10% in urban areas could keep extreme surface temperatures at current levels up until the end of the century, despite climate change [21].

Biodiversity Older gardens and parks often contain noticeably rich biodiversity [59]. These are the main habitats of urban plants and animals. Older, well-established installations attract, for instance, birds and mammals, the natural habitat of which is the forest. Since an increasing part of the population lives in urban areas and receives its daily perception of nature therein, nature in urban areas is important to environmental awareness and an understanding of nature.

Urban landscapes create new habitats for species establishment and germination and colonization sites [86, 89]. These new habitats can affect biodiversity and change community structure. Although an urban landscape may not have a full complement of natural species, the existing natural and seminatural ecosystems can provided a suite of benefits compared to the urban built infrastructure and other technologies.

Economic Functions

The aim of sustainable development is to meet the needs of both present and future generations by promoting development that does not degrade the environment and is technically appropriate, economically viable, and socially acceptable.

Food from trees in private gardens, fruit orchards, or allocated plots in public gardens can contribute significantly to food security in developing countries [41]. Low-care wild edible plants are often excellent candidates for multipurpose use as ornamental roadside plantings. Older fruits varieties in aging orchards are an important genetic repository.

Woodfuel provides between 25% and 90% of urban household energy supplies; it is particularly important as a source of energy in smaller urban centers in developing countries, especially in dry zones [41]. Poor urban households spend a significant proportion of their cash income in obtaining wood energy. If the urban poor population continues to grow, an increase in the consumption of traded woodfuel is likely to be a consequence. Under favorable circumstances, fuelwood from non-rural forests and agroforestry systems can contribute significantly to fuelwood supply.

In rich countries, urban green spaces can contribute to the local economy, by enhancing real estate prices and by attracting economic activity and improving the local tax base. Several Scandinavian studies show that the prices of apartments are significantly raised in the presence of nearby woodlands or other types of green space (e.g., [81]). Trees and greenspace also help to conserve global energy reserves in developed nations where they are consumed at the greatest rates.

Social Functions

Health Aspects City life is stressful, but research shows that urban green areas have a beneficial influence on the health and well-being of the urban population. Several studies conducted in Europe and the USA indicate that visits to green areas can counteract stress, renew vital energy, and speed healing processes [56].

Kaplan and Kaplan [32] formulated a theory on the interaction between man's attention and his surroundings. This means that urban living, with fast vehicles, flashing neon signs, and strong colors, causes constant stress. The research indicates that vegetation and nature reinforce one's spontaneous attention, allow one's sensory apparatus to relax, and infuse one with fresh energy. Visits to green areas bring relaxation and sharpen one's concentration, since one only needs to use one's spontaneous attention. At the same time, one gets fresh air and sunlight, which have significance for one's diurnal and annual rhythms.

Furthermore, Ulrich [83] showed that hospitalized patients recovered faster when they had a view through a window, allowing them to see trees. In 1991, he conducted a new study showing a gory film on industrial accidents to 120 people [84]. Half of the people were then shown a nature film, whereas the other half were shown a film on the city, with sequences of buildings and traffic. The subjects' heartbeat, muscular tension, and blood pressure were monitored throughout. All subjects exhibited strong signs of stress during the first film, on industrial accidents. The stress levels of the half of the subjects that then watched the nature film had returned to a normal level after 4–6 min, whereas the half that watched the film on buildings and traffic continued to exhibit high stress levels.

Another important health function is recreation provided by parks in areas that are used for recreational activities such as walking, biking, and spaces for children to play. Finally, when several metric tons of air pollutants are removed by urban forests in Mexico City, this also can lead to substantial health benefits [14].

Educational Functions Closely related with the ecological and social values of urban green spaces is their educational function. Since a rapidly increasing part of the world's population lives in urban areas and receives its daily perception of nature therein, nature in urban areas is important to increase environmental awareness and an understanding of nature.

Richard [45] coined the term *nature deficit disorder*, to refer to the trend that children are spending less time outdoors resulting in a wide range of behavioral problems. He claims that causes for the phenomenon include parental fears for their children in urban areas, restricted access to natural areas around cities, and the lure of the computer and television screen. Result of nature deficit disorder can include childhood obesity, attention disorders, and depression. Providing youth time in nature during the school day can help reduce anxiety and have a positive effect on the attention span, stress reduction, creativity, cognitive development, and children's sense of wonder and connection to the earth.

Urban Forest Policies

Urban Forest Policies Defined

A policy is a generally agreed-to and purposeful course of action that has important consequences for a large number of people and for a significant number and magnitude of resources [12]. Policies can be informal as well as formalized in written documents. Usually policies are selected from a number of alternative courses of action – by government agencies, as well as by institutions, groups, and even individuals.

Drawing on the political sciences, Ottitsch and Krott [58] mention three central concepts for strategic decision-making about urban forests. "Polity" comprises the institutional dimension at formal levels relating to, for example, constitutions, laws, taxes, parliament, as well as at informal (e.g., traditions) levels. "Politics" then refers to the procedural dimension, looking at the dynamics of political processes, as, for example, concerning will formulation, interest mediation, bargaining, and communication processes. "Policy," finally, refers to the substantial or normative dimension, which includes issues and objectives as well as outcomes of the political process. A policy document can be a typical outcome of the political process.

While politics and policy-making relate to the choice of and releasing of certain political decisions, planning encompasses a search for implementation options [34]. Planning has also been described as coordinating management in order to meet the objectives the community would like to see met [58].

In an urban forestry context, policy-making and policies define the strategic choices regarding urban forests, typically for a period of at least 10 years. These typically relate to which urban forest functions should be in focus, depending on societal demands. But urban forest policy-making is also about how to conserve and develop urban forests in highly dynamic, high-pressure urban settings. Conflicts are an integral part of urban forestry, and, not surprisingly, urban forest policy-making has thus been defined as a social bargaining process between stakeholders for the regulation of conflicts related to different interests concerning urban forest utilization and protection [58].

As urban forests comprise a form of urban land use, planning helps to relate urban forest to other types of land use, as well as helps guides choices within urban forest areas. Planning can be seen as the intermediate level between decision-making (policy) and actual implementation of decisions. In urban forestry, the latter comprises, for example, the design and management activities described elsewhere in this chapter.

Urban forest policies and planning deal with a highly complex field, with a large variety of actors in play. Complexity also relates to the complexity of the urban forest itself. As is seen, it constitutes an overall green network that includes tree elements ranging from street trees to large woodland areas.

Urban Forest Policies and Plans Today

Research has shown that across the globe, urban forest policies are scarce when regarded in terms of formalized policies that specifically focus on a city's "urban forest," incorporating all tree-dominated vegetation [34, 60]. A growing number of cities in especially the industrial world have developed policies and strategies for (part of) their green spaces, as, for example, reflected by green structure plans. Green belt policies inspired by the London Green Belt have been in place in many parts of the world [2]. But a strategic perspective on what should happen with a city's woodlands and trees is seldom present. Exceptions are North American and British cities with specific urban forest plans. The most typical level of plans, however, has been that of (park and forest) management plans which pay less attention to strategic, longer-term decisions, and focus more on short-term, operational maintenance tasks. There are exceptions, however, such as the strategic management guidelines developed for forests in and near major German cities.

As urban forest policies are largely absent at the local level, it is not surprising that they are even more scarce at the national level. Still, some national urban forest policy-making has occurred, with countries such as the USA and China as important examples. In the USA, a nationwide urban forestry program has helped raise political awareness about urban forestry, as well as aided implementation of urban forestry at state and local level (e.g., [13]). Moreover, the national program has been supported by substantial research funding. In China, urban forestry and urban greening policies have been developed by the national government. As part of the national programs, cities with ambitious and successful greening programs being awarded awards and privileges [43]. Elsewhere, countries such as Malaysia and Singapore have developed ambitious national "greening" programs (e.g., [60, 77]) in which tree planting plays a major role.

In Europe, the UK has probably been the country with the most ambitious urban forestry policies. Urban and community forests were described as a priority and powerful tool in the England Forestry Strategy issued in 1998 [18]. In a national program called the Community Forest Program, woodland establishment and management near large agglomerations has been used to tackle significant social, economic, and environmental challenges [36]. The Community Forests were set up as partnerships between national and local public bodies, as well as a range of private actors. When focusing on the woodland element of urban forests, the last 2 decades have shown a boom in new policies that have incorporated the importance of urban forests and/or urban forest elements. Countries such as Belgium (Flanders), Denmark, Ireland, Netherlands, and Great Britain issued afforestation policies in which urban agglomerations have the highest priority. Woodland grant schemes thus favor urban settings. Social and environmental services such as providing opportunities for outdoor recreation and protection of drinking water for primarily urban populations have become prioritized in national forest policies.

At the international level, the Food and Agriculture Organization (FAO) of the United Nations started to actively engage with "urban and peri-urban forestry" during the late 1980s. From the late 1990s, efforts intensified (e.g., [38]). FAO, for example, assigned a series of urban forestry case studies in the developing world, demonstrating that urban forestry was not only a promising approach for western countries, but could help developing-country cities in dealing with environmental and economic challenges. FAO also assessed the status of urban forestry legislation and released a series of guidelines for good practice in, for example, urban forest policy-making. Urban forestry became integrated in the so-called Regional Outlook Studies for forestry, starting with the Forest Outlook Study for West and Central Asia [17].

Policy objectives for urban forestry have changed over time, in line with changing societal demands and focus on different urban forest benefits. During a large part of history, for example, especially urban woodland was conserved and managed as provider of local timber, fuelwood, and animal fodder [36]. City forests such as the Sihlwald near Zurich, Switzerland, for example, were gradually "annexed" by the neighboring city eager to guarantee a steady supply of timber for construction. Urban woodland areas were also protected by kings and other rules as hunting domains. Throughout history hunting was not only a favorite pastime of those in power but also a means of obtaining status and prestige. Prestige was also an important reason for developing the first city parks and boulevards, inspired by the work of Haussmann in Paris.

Over time, urban forestry became targeted toward a wider range of users, with the benefits of green space, for example, for public health and worker well-being becoming recognized in the industrialized world. Recreation and other social benefits came in focus – where they still are today, as described elsewhere in this chapter. This can be illustrated by various studies of urban forest policies in Europe (e.g., [34, 58]). The social benefits of urban forests are prioritized in most cities, with environmental services such as protection of drinking water, improving the urban climate and nature protection ranking second. Economic benefits in terms of, for example, timber production is only of secondary importance in most western cities, although several cities in, for example, Central Europe do manage their forests for timber. Moreover, new focus on bioenergy as alternative to fossil fuels also makes wood harvesting more attractive once again [36]. In developing countries, urban forests often make important contributions to local livelihoods.

Although there seems to be agreement that urban forests primarily have amenity values, this does not mean that conflicts over the green spaces and their use do not occur. In fact, urban forestry policy-making is very much about managing conflicts, for example, between a range of different recreational uses. Relatively small areas of urban forest near to cater for the wishes of thousands and sometimes millions of people.

Conflicts are also mentioned as an important element of urban forestry policies and planning by Ottitsch and Krott [58] in their study of urban forestry policies and planning in 14 European cities. They describe a number of common elements apart from a joint focus on social and environmental benefits. The authors stress the importance of municipal land property and regulative policy instruments – and the fact that current urban forest policy mostly deals with publicly owned land, even though a considerable part of a city's urban forest is in private ownership (e.g., private garden trees). In the case of private ownership, public authorities use legislation such as tree protection orders and financial instruments such as subsidies for private land owners offering recreational access to their lands.

Actors and Stakeholders

From a "polity" perspective, municipal authorities are the main decision-makers for urban forests. The strong role of municipal actors is partly due to what Ottitsch and Krott [58] call the traditional "property strategy" according to which city governments attempted to transfer green space within their boundaries or within their otherwise described spheres of interest to municipal property.

In spite of the dominant role of municipal governance, however, decision-making about urban forests is seldom a comprehensive process with one central actor. Typically, different components of the urban forest are the responsibility of different municipal departments. Comprehensive policies are difficult to develop, as city trees, parks, and woodland areas are often placed in units or divisions each with their own culture and way of doing things. As Liu [43] has shown for the Chinese city of Weihai, city park and forestry units have had difficulties in cooperating or at least followed their own agendas. A trend in many European countries has been, however, to integrate the different green space elements (e.g., parks, nature areas, and forests) in one division or department, something which could be expected to lead to more comprehensive urban forest policies and planning.

Other public actors also play a role in urban forestry decision-making, especially through state forest agencies that manage forest areas surrounding cities and towns. In some cases, state forests are even part of the city proper. Often these state forests are former royal hunting domains [34].

Private land owners do play a role in urban forestry, for example, through privately owned wooded estates. Moreover, a large part of a city's tree population is typically located in private gardens.

In addition, urban forestry policy-making and planning involve a wide range of other stakeholders. Obviously residents and users play an important role, as primary beneficiaries of urban forestry. Participation and communication regarding urban forest issues has steadily increased during recent decades. As Moll [52] states, "Where we find healthy city forests, we usually find strong citizen support. In the end, the support of city managers and government agencies comes back to citizens. They are the conscience of the community and the clients all political leaders work for. No other group feels the sense of place trees offer of organizes a force to change conditions more effectively than citizens. City forests decline when city foresters consider citizens a group to avoid, and the forest improve when lines of communication are opened." Although public participation has been increasingly called for in urban forestry, it is not always a well-developed component of decision-making processes [58, 85]. Another important group of policy actors are nongovernment groups such as nature conservation and outdoor recreation associations.

Policy Integration and Governance

Urban forest policy-making and planning are changing in response to a series of challenges to urban forests and local authorities. Ottitsch and Krott [58] speak of a number of "tension lines" in urban forest policies. In many cases, as described, there are no comprehensive policies for urban forests, but rather a patchwork of segmented policies, different spheres of interests, and competition between different municipal bodies. The role of urban forestry as a public service is also under debate. Urban forests are seen as a public service and public good, which has led to focus on expensive property strategies. In a time of public budget cuts, alternative funding mechanisms and policy instruments need to be developed. Conflicts over urban forests (and their use) have intensified and urban demands are rapidly changing.

However, urban forestry also involves a range of promising opportunities. The role of trees and other vegetation in tackling major political issues such as climate change mitigation and adaptation, promoting human health and well-being, and enhancing city competitiveness in a globalized society is increasingly recognized. Forests and trees can play a role in large, market-driven development projects, for instance for new sustainable urban development schemes. Through the strong associations people have with forests and trees, these can play an important role in symbolic communication. One example is representing a physical sign of how the local environment is improving [42]. This symbolic role has been intensively used in programs such as the English Community Forests, but also in the "rebranding" and greening programs of a city like Chicago. In a time of, on the one hand, individualization, and on the other hand migration, urban forests are among the final truly public areas where all of society's segments and groups can meet each other. Thus urban forests can help strengthen social cohesion (e.g., [62]).

Developing the potential of urban forestry requires closer collaboration between stakeholders. Municipal authorities alone can no longer manage the task alone, hampered by government reform, lack of finances, and calls for greater involvement. New modes of governance are needed – with governance being defined as the process of making decisions that define expectations, grant authority, and verify performance [33]. In urban forestry, the traditional approach of "governance by government" needs to be (and is increasingly) replaced by modes of "governance with government," as, for example, reflected in public–private partnership and public involvement processes.

New forms of governance for urban forests are being explored. In Finland and Sweden, for example, National Urban Parks have been established. The Stockholm National City Park, which includes the Norra Djurgården city forest, was the first of its kind. The park, established by parliamentary decision in 1994, is the result of new environmental and land use legislation and the national level. National urban parks are developed as a partnership between state and municipal authorities, as well as other stakeholders. The overall aim for the NCP is to act as a model for sustainable development, with focus on nature and ecology, recreation and culture. Swedish legislation stipulates that national urban parks should contain natural areas important for the preservation of urban biodiversity, cultural milieus – including buildings – important for an understanding of national history or that of the city itself, and parks and green areas of architectural or esthetic significance [71]. Multi-stakeholder schemes for urban forests of national as well as local importance also include the Biosphere Reserves developed near cities from Vienna to Sao Paolo [36].

Urban forestry can "feed in" to emerging, integrative planning approaches such as "green infrastructure planning." The term "green infrastructure" has become frequently used in countries such as the UK and the USA in reference to urban renaissance and green space regeneration. It can be defined as creating networks of multifunctional green spaces that are carefully planned to meet the environmental, social, and economic needs of a community [44]. All green spaces, both public and private, are considered. By using the term "infrastructure," focus is on functionality and green spaces enter the urban planning discourse at an essential public service.

Design and Management of the Urban Forest

As reflected in the overall concept of urban forestry as described above, design and management of urban forests is an interdisciplinary and participatory field at the interface of, among others, landscape architecture, landscape planning, horticulture, arboriculture, forestry, ecology, and the social sciences. Whether urban forest elements are of natural, seminatural, or man-made origin, and whether new elements need to be added to the urban green structure or existing components require changes due to evolving demands, proper design and management are needed to ensure that woodlands, parks, and trees in streets and other urban spaces can provide the environmental, economic, and social functions society attributes to and demands from the urban forest resource. The disciplines, professions, and stakeholders involved vary depending on the location, setting, and social and cultural context, and not at least on the type of urban forest element concerned.

Across the world, urban forest design and management relate to very different circumstances. The climate, the ecosystem, the character of the people, the cultural history, city development, and the political settings over time varies between cities, between regions, between countries, and between the continents. Design and management aim to maintain and incorporate the rich variety of climate, ecology, tradition, and cultural heritage contained in the existing resources, whilst at the same time meeting current demands and incorporate flexibility for changes in future requirements (population pressure and social values) and climate (climate change) [5].

Many of the most appreciated urban woodlands, parks, street tree plantations, and private gardens are characterized by old and graceful trees recognized for their cultural–historical and natural values. An inventory of the Belvoir Park Forest at the fringe of Belfast, Northern Ireland, for example, found 270 single stem trees with a diameter at breast height of 3 m or more [75]. Such trees act as landmarks and offer important habitats for biodiversity [31] and management often aim to maintain them for as long as they do not pose a security risk [28]. Design and management of urban forest therefore have to consider the full life cycle that trees have in nature, including developing stages of establishment, growth, early maturity, and degrading stages of late maturity and degradation, and today continuous design and redesign over time is perceived as a crucial part of sound, sustainable urban forest management [5, 25].

Whereas the urban forest traditionally has been designed and managed with the mature stage in mind only [24], the pace of urbanization and social changes leading to cities being transformed and renewed faster than trees can grow, has resulted in a changed professional mindset. Design is increasingly perceived as a continuing process rather than a one-off action. It is seen as a crucial part of sound, sustainable management [5, 25]. This has led to an upsurge in integrative and adaptive approaches in urban forest design and management that focus on developing qualities through all stages of development, from establishment and growth through maturity and to degradation (e.g., [10, 53]), while in streets, squares and other "gray spaces" the demand for "instant" values have implied that planting of large trees of 20–30 cm circumference or more, is becoming increasingly common practice [79].

Design of urban forests operates on different levels [5]. At the integrative and strategic level, design operates on the regional scale where urban green areas are linked to the landscape structure of the wider region, such as the "Finger Plan" of the greater Copenhagen area in Denmark. At the city level, urban green structures are designed to give strength and depth to the urban forest by linking individual components and their form and functions. Frederik Law Olmsted's design of the "Emerald Necklace" in Boston, Massachusetts, from the 1870s is one of the first and most known examples of design constituting a green infrastructure. At the site level, the form, structure, and content of individual green spaces are designed with linkages to local aspirations and use patterns, including the detailed layout and use of different vegetation elements, such as the number of plants involved, what types they are (trees, shrubs, herbaceous plants), the mix of species, how the plants are assembled in space, and their age or maturity.

The concept of urban forest management relates to management as operations and management in terms of organizations carrying out the management [25]. Municipal authorities are the main managers of urban forests but following the introduction of New Public Management doctrines a growing number of cities in especially the industrial world have outsourced management to private enterprises (e.g., [65]). Trees in private or commercial spaces such as gardens or business premises often represent a significant proportion of the tree population of a town or city. Although it is difficult to control how trees on private property are used and managed, urban foresters are increasingly becoming aware of the need of including them in the complete urban forest resource. During the last decades many cities throughout the world have developed and implemented orders and legislations that protect and prohibit removal or damage of trees in public and/or private areas by use of, for example, felling licenses, replacement planting regulations and enforcement systems such as penalties [64, 73].

Management operations address different levels. Gustavsson et al. [25] write "At the level of strategic management, the overall visions for management are developed. In line with policies and planning, objectives and targets are formulated, means are allocated and a time frame is set. Specific, well-defined tasks are defined and carried out in line with this at the level of operation management. While strategic management typically addresses a period of 10 years or more, operational management focuses on annual or biannual activities. As an intermediate level, tactical management brings the two together."

Design and management of urban forests are directed by objectives and targets, economic and other frames, and not at least the type of green area concerned. The variety of urban situations that trees relate to has been grouped into three types [66]. The first type of location is trees in street, square, and other "gray spaces" with sealed surfaces. The second include parks and other green spaces such as yards, gardens, and commercial areas. The third is stands of trees which are referred to as "woodlands" or "woods" to distinguish between the wider urban forest resource and its components that have traditionally been defined as "forest." The main design and management issues, concepts, and principles vary between the three types of locations.

Trees in Streets and Other Paved Areas

Row plantings of uniformly spaced trees are one of the earliest and simplest expressions of intentional and functional design. Over the ages, trees have been an integral part of the urban infrastructure and a mirror of the prosperity and achievements of society, such as the *Platanus* alley in the Agora of Athens, 500 BC. In Europe, the use of actual street trees became more widespread following Haussmann's renewal of Paris during the 1850s and beyond. Here trees became substantial street fixtures perceived as providing important esthetic and climatic benefits [49], and today systematic tree planting in streets and boulevard is a powerful characteristic of the city.

Trees in streets and paved areas are an important component of the urban forest, as well as an important architectural element in the cityscape where they ameliorate esthetic, social, and microclimatic conditions [3]. The natural, graceful shapes of trees provide a transition between human size and the scale of buildings and streets, as well as an element of continuity and uniformity in heterogeneous districts of mixed uses, building styles and variable scales [5]. Trees can be designed to relate to built form in different ways by use of different architectural principles of scale, massing, enclosure, and perspective, by use of different design concepts (e.g., boulevard, avenue, alley, single line, block, grid, or groups design) as well as different functional characteristics related to tree from size, texture, color, and different degrees of light and shade [3, 20]. In many cities, the "web" of trees along streets, squares, etc., weaves through the city and supports the overall sense of a citywide forest by creating ecological corridors and visual links between woodland, parks, and other open spaces. In the historical or commercial core of larger cities, streets and not in the least parking areas are often the only location available for trees. In countries with a warm climate, the shade provided by trees encourages life to take place in the street.

Streets and other paved urban areas with surface sealing are generally characterized by limited space for planting pits, alkaline and compaction soils resulting from construction work, utility trenching, and in the many parts of the world use of deicing salt. The complex stressed environment challenge tree growth [74] and integration of adequate spaces and growth substrates in the overall street design is increasingly called for [61, 76], as is the use of stress-tolerant tree species (e.g., [4, 79, 80]). In the Central European region, an important contribution is the Climate-Species-Matrix developed by Roloff and colleagues [67] to support choice of tree species for urban habitats considering climate change. The matrix contains 250 woody species used in Central European green spaces. Based on drought tolerance and winter robustness, each species is assessed and classified with regards to usability after predicted climate changes of increased average temperatures and more frequent heat waves and periods of drought.

Research has shown that a limited number of tree species dominate the tree stock in streets, but drawing on the severe consequences of Dutch elm disease a growing number of experts emphasize the use of a diversity of species as key component of design strategies aimed at increasing the resilience of the tree stock to pests and diseases [4, 51]. The most comprehensive recommendation of the latter concept is provided by Santamour [70], who suggests that no species should represent more than 10%, a genus not more than 20%, and a family not more than 30% of the population.

Besides selection of suitable tree species and proper design and planting, aftercare is essential to maintain healthy, esthetic, and safe trees in the harsh conditions of streets and other urban paved sites. Urban tree management techniques and activities are grouped under the field of arboriculture, that is, the cultivation and management of individual or small groups of woody plants, primarily in urban areas. Arboriculture includes watering, fertilization, mulching, protection with (stakes, supports), and formative pruning of young plantings, as well as training, vitality, and safety inspections of mature trees to reduce hazard [9]. It is based on a detailed understanding of tree biology and responds to cultural practices of pruning and to wounds and environmental conditions. Arboriculture also plays an important role in management of trees in parks, gardens, and other urban green spaces, but here, management of other types of vegetation also comes in.

Parks and Other Green Spaces

Parks, gardens, and other urban spaces dominated by vegetation often contain a considerable number of trees, but actual forest stands are often limited or absent. Instead elements such as lawns, pastures, garden elements such amenities as seating and different types of infrastructure and/or buildings dominate [5]. Design and management aim to integrate elements into attractive areas that are enticing for people of all ages, genders, and backgrounds, and stimulate use on regular basis during all parts of the day, week, and year, where trees are used to provide ornamental values as well as mass and structure and define the character and scale of space.

Park design has evolved through a number of phases where different styles have reflected the social, cultural, and artistic movement of the times when they were created. Beautification has traditionally been one of the main arguments for greening cities with parks, gardens, and other types of green spaces [36, 82]. The park first became an integral part of city planning and development in England during the 1830s, and then subsequently spread throughout Europe, North America, and eventually the world. In the polluted and densely populated cities that followed the industrial revolution, parks were seen as a solution to both social and hygienic problems. Peoples could gather and socialize in the fresh air, which promoted public health [8]. Playgrounds, sports fields, and other facilities stimulation activity evolved as one of the most important features of public parks, and remain so today. Yet, as evidence has mounted about the multiple functions urban green spaces provide, their design and management has gradually shifted to also encompassing environmental, conservation, and economic benefits with the aim to develop functioning ecosystems as well as settings for cultural and social activity [5, 25, 47].

Recognizing the interconnection of natural resources and human resources and design and management of parks and other green spaces have become essential for the concept of sustainable urban ecosystems. The political movements of sustainability and protection of biodiversity have caused a more restricted use of the richness of exotic species, which for centuries have been a predominant element in park design due to their ornamental values. The focus of decision makers, professionals, as well as residents on protecting local nature and cultural history have implied that the design and management of urban parks and woodlands increasingly are carried out as part of varying restoration programs which either concentrate on ecosystems functions or cultural history, or both (e.g., [22]). One example is the "Isar Plan," where the strongly regulated Isar river course in the inner-city of Munich, Germany, has been redesigned as part of a program that combines flood protection with the restoration of a near-natural river landscape and the improvement of nature-oriented leisure and recreational use of the urban population in the river bank zone [16].

Trees in private or commercial spaces such as gardens or business premises often represent a significant proportion of the tree population of a town or city, and give people the chance to express themselves and to develop their own, personal relationships with trees and plants. Although it is difficult to control how trees on private property are used, urban foresters are increasingly becoming aware of the need of including them in the design and management of the complete pattern of urban woods, parks, street trees, and trees in private spaces [5]. In recognition of this, an increasing number of cities have developed tree protection orders that also include private trees [64, 73], as also described elsewhere in this chapter.

Woodlands

Urban woodlands are designed and managed for a variety of purposes. Originally, provision of timber and fuelwood was the main reason for cities and towns to own and manage forests, but this function is presently only of secondary importance [36]. Recreation and nature protection typically are the main functionalities of urban woodlands today [5, 82]. Woodlands tend to be more multipurpose than parks and other urban forest elements, and their design and management need to accommodate more uses, some of which might conflict. Aspiration of woodland character differs greatly between users, for example, according to age, sex, profession, and cultural background, and it is important to consider the social status and recreational use of the individual woodland as well as the ecological status and potential for nature conservation, and to rank the use priorities when deciding on their design and management [28, 46].

Bell et al. [5] define woodland design as "...accomplished through the manipulation of the spatial pattern of different stands of trees, their species composition and vertical structure(...) These elements are manipulated through woodland management and the adoption of different silvicultural systems." However, the importance of urban woodlands has from a silvicultural perspective been widely overlooked and approaches that are suited to the capacities of woodlands and the realities in urban contexts are still under development. Much urban woodland has developed over time from commercial production plantations and mainly consists of even-aged monoculture types with interiors resembling the "pillared hall." However, canopy trees, undergrowth, and the main characteristics of the ground flora are all of importance for biodiversity and for the human experience of character, size, and atmosphere of forest interiors [25]. Municipal authorities throughout Europe and North America are increasingly applying a variety of management techniques to achieve different structures of vegetation and atmospheres within individual woodlands as well as across woodland lots. Form- and species-rich forest stand types associated with selection cutting methods are considered among the most valuable types to integrate high esthetic and biological qualities [25, 90], especially in smaller-scale woodland lots. Historical/cultural forest management regimes, such as coppice forests, forest pastures, and unmanaged forests are also increasingly applied to assist diversifying woodland interior rooms and habitats within and across urban woodlands for the benefit of people, plants, and wildlife [25, 54, 69]. Natural colonization has also been identified as a management tool that can give strength to urban woodland design and that is readily transferable, although regional differences have to be taken into account [68].

Compared to "commercial" forests with a management regime aimed at wood production, and where the stand is the functional unit, the higher functional level – that is, the woodland landscape – is of equal importance when it comes to developing recreational and ecological functionalities in urban woodlands [25]. Hence, design and management of urban woodlands should not only give attention to stands, but also to the wooded landscape. Variation between wooded areas and open habitats and recreational areas is a common characteristic for many of the most appreciated and well-known urban woodland landscapes in Europe, such as Amsterdamse Bos, the Netherlands, Helsinki's Central Park, Finland, and Jægersborg Deer garden north of Copenhagen, Denmark. The mosaic of interiors under closed canopies, intimate glades, and canopy openings, semi-open savannah-like areas with scattered trees, open spaces of varying sizes and types and a diversity of edges along the boundary of forested and open parts are mutually supportive for multipurpose uses [5], while they also create habitat diversity, something which is of the utmost importance for biodiversity conservation.

Urban growth has in many cases led to woodland fragmentation, cutting woodland areas into more or less isolated patches of varying sizes, ranging from small copses and woodland remnants to large wooded landscapes. This fragmentation should be considered when designing and managing urban woodlands. While larger woodland landscapes are often the most used for recreational purposes, small wooded lots account for a large share of the woodland resource in many cities. In the case of Ljubljana, Slovenia, for example, Pirnat [63] idenfitied as much as 606 woodland lots of a size of 0.5–10 ha. While woodlands in general are able to absorb many uses, small woods limit recreational as well as ecological opportunities whilst larger woods can absorb many uses and provide a wider range of ecosystem services [1, 5]. Zoning different functions and applying different silvicultural systems in order to separate and provide attractive and safe environments for various forms of recreation and ecosystem functions within woodland lots and across the diversity of urban woodlands are frequently applied [19, 23, 69].

Urban Forest Information and Inventory

To support sound urban forestry programs, policies, planning design, and management, high quality information is needed. Schipperijn et al. [72] divide the wide range of information requirements into basic green space information, environmental and ecological information, and sociocultural information. The need for reliable information has led to the development of different methods, tools, and systems, such as remote sensing, tree inventory systems, biotope mapping, sociotope mapping, GIS systems, and decision support systems to help collect, compile, and use available information, many of which are described in Schipperijn et al. [72]. Following the introduction of New Public Management doctrines, an increasing number of cities in especially the industrial world have outsourced urban green space management or implemented internal division of purchasers and providers in order to reduce management costs and to gain more insight into the daily management routine tasks and costs (e.g., [65]). In this process, detailed inventories and monitoring have been carried out to establish "basic green space information" about the location of green areas, green elements, and street trees, characteristics and quantity of different elements (species, age, size, height, and so forth), as well as information on type and quantity of the different management activities in use. In comparison, inventory and monitoring providing "information about the environmental and ecological" conditions that influence green spaces, as well as the environmental benefits of green spaces are still under development and implementation, as are methods for collect and compile "sociocultural information" dealing with user preferences, cultural values, economic benefits, and information on health and other social services.

Future Directions

The world's urban population will only increase in the coming years, which means that the focus on cities as sustainable human habitats must increase as well. There will be a growing need for research and policy support in the field of sustainable urban development. What should cities of the future look like? What constitutes a "good city"? How much green space is necessary to sustain a healthy population? Each city has its own specific problems, mainly related to economic status and geographic location.

At present, research results indicate that the urban population in general would benefit from a well-developed green infrastructure, especially when the urban green space is well integrated in the overall city planning. It is important to realize that planting more trees or creating more green in urban areas is not enough. Studies indicate the importance of well-funded, long-term management and proper maintenance of the green infrastructure. It is also clear that public participation ensures the success of government investment and is an important tool in providing sustainable green space and in creating sustainable cities.

The increased interest in urban ecology and environmental problems will drive investment in parks and green areas over the coming decades. Most of these should be laid out in the larger and rapidly expanding cities of Asia, Africa, and Latin America to ensure an equitable distribution of green space and healthy, sustainable population growth. Similar expansion of protected green infrastructure was carried out in North America and Europe during the years after the Second World War and up to the 1970s. Planning has not kept up with growth in many cases, and the need exists to look at a mega-regional scale to identify remnant urban and peri-urban open space and critical lands for protection that will be sufficient to supply a steady source of ecosystem services to sustain long-term population growth. Over the coming years, the main challenge will be to ensure that the expansion of green infrastructure in the world's urban areas is implemented within the framework of sustainable development, optimizing the ecosystem services provided by these natural resources with the use of appropriate technology, community participation, and without a heavy dependence on chemicals and irrigation. This will ensure that the rapidly expanding urban landscapes remain resilient and healthy habitat for a growing society.

Today's focus on climate change will raise the demands for more compact cities. But a compact city with a lot of sealed surface and lack of green space is very vulnerable for the effects of climate change. Therefore, the issue of urban density is a good example of a potential conflict between mitigation and adaptation concerns. If increasing density, in order to reduce energy by lowering travel demand and heating requirements, leads to the consumption of green space resources, its consequence will be the loss of a vital adaptation resource. The concept of the city of tomorrow is such an oxymoron. The challenge is how to combine the need for a compact city with people's need for green space close to where they live – The Green Compact City. *Inter alia* Scandinavian planning and building tradition contains several examples which could inspire. Better coordination between transport, land use, and open space planning; urban containment and preservation of the green infrastructure; the creation of new urban landscapes; and promotion of the urban–rural interface are basic principles for this. Urban forestry is one of the promising approaches to support this process.

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Urban Redevelopment and Quality of Open Spaces

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Article Outline

Glossary

Brownfield Brownfield is an usused urban site of derelict or underused land, which require intervention to bring it back to beneficial use and which may have real or perceived contamination problems (see also: http://www.cabernet.org.uk).

Perforated city The concept is used in the sense of a city whose physical fabric contains a scattering of vacant sites and which is undergoing progressive redistribution.

Renaturation The concept is employed here not in the narrower nature conservation sense but as used by the Federal Ministry for Building, Transport and Housing, and the Federal Office for Building and Spatial Planning to refer to urban redevelopment projects that are basically concerned with the temporary or permanent downzoning of building land into green and open spaces [36].

Shrinking city Shrinking City can be defined as an urban area that has faced a population loss in large parts of it for more than 2 years and is undergoing economic transformations with some symptoms of a structural crisis.

Urban Redevelopment Program "Stadtumbau Ost" ("Urban Redevelopment East") Federal funding scheme in Germany which has the aim to demolish a certain number of flats in order to regulate the housing market.

Definition of the Subject

Urban shrinkage has become a new normality for a growing number of European cities and urban regions. It is a result of different but strongly interconnected processes: uneven economic development, demographic change, shifts in land use and urban form, as well as housing preferences and lifestyles. Shrinking urban regions develop their own patterns of development, and form distinctive dynamics that differ from those of their growing counterparts. Shrinkage, however, produces brownfield sites or open spaces of various sizes practically everywhere in the urban fabric. Many local authorities engage in scattered downsizing within existing settlements. But this type of urban redevelopment reaches its limits when "holes" steadily multiply and the physical urban fabric disintegrates. Redevelopment and downsizing raise the question of how the design of open and green space can provide a new quality of urban development. The major issue for the future is how public funding can best be deployed in handling vast areas of previously developed land within increasingly perforated cities. This paper looks systematically at the solutions already available and what contribution they can make to improving the ecological quality and the quality of life in cities.

Introduction

The current discussion on shrinking cities stresses the long-term nature and irreversibility of shrinkage, necessitating the abandonment of long-established planning principles. Furthermore, note is repeatedly taken of the fragmentation and perforation of urban areas, caused not least by parallel shrinkage and growth. However, the discussion has focused primarily on housing and to some extent on infrastructural problems. Abandoned industrial land and new brownfield

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sites in residential areas, in contrast, tend to be given only cursory attention – they are literally a "marginal problem."

Shrinking cities are not a new phenomenon, but in the past they have been regarded only as isolated or regionally limited exceptions [1]. During the last decades shrinking cities have become a distinct urban process in particular in Europe [2]. While a considerable share of "urban Europe" has been growing during the last decades and continues to do so, other urban regions have been suffering from deindustrialization, population loss and decay for decades. Nearly one third of all of Europe's cities with more than 200,000 inhabitants have at least undergone one decade of population decline [3] in the last 45 years. Whereas some of these cities have been losing population ever since the 1960s, the majority of cases started declining only in the 1980s and 1990s. While population losses and economic decline can also be found in numerous Western and Southern European cities, they are especially pronounced in Central Eastern and Eastern Europe [4]. Here, declining urban population numbers are rather the normal case than the exception [3]. It is a result of different but strongly interconnected processes, that is, uneven economic development, demographic change, as well as shifts [5] in land and resource use, urban form, housing preferences, and lifestyles. As these drivers of shrinkage will increasingly impact on urban and regional development in the future, shrinkage clearly represents a key regional development challenge in Europe. Recent statistics show that processes of shrinkage will even gain more importance over the next decades: According to estimations by the UN, the population of western, northern, and – most of all – southern Europe will decrease. Current calculations of the UN predict a decline in Europe's population from 729 million in the year 2000 to 628 million people in the year 2050.

Shrinkage has thus not only become a new normality for a growing number of European cities but a serious challenge for urban planning. In many cases, shrinkage is caused by the sudden vacating of waste sites or a systematic retreat from extensive development in the course of redevelopment. The question of the quality and use capability of the (new) open spaces therefore takes on new dimensions: How can or should previously developed land be integrated into the urban fabric? What contribution can it make to local residential amenity? What interim and after-uses can be envisaged?

This paper looks at the dimensions of shrinkage and vacancies in East Germany, where this process is in particular pronounced due to the interaction of outmigration, demographic change, and suburbanization. As a reaction to the shrinkage processes in East Germany, the federal government established the "Urban Redevelopment East" program, which seeks to create solutions to this development. It also investigates how open spaces in shrinking cities are treated, what solutions have hitherto been adopted, and what approaches are desirable from an ecological, social, and/or economic point of view. Examples are presented from various cities in East Germany. The idea of the paper is that these solutions are applicable as well in other European cities or worldwide.

Dimensions of Shrinkage and Vacant Land in East Germany

In East Germany, 90% of all towns and cities with over 20,000 inhabitants have suffered a population decline ([6]; [7], p. 62). Shrinkage in such dimensions and at such speed is a new phenomenon in Europe [8].

It follows on from a process that began in GDR times. Between 1949 and 1989, the German Democratic Republic lost about two million inhabitants. Local authorities also lost population owing to government-planned concentration processes, so that there were old gaps in the fabric of many towns and cities, often in a derelict state. At present, three main processes are causing shrinkage in East Germany: (1) the deindustrialization that set in with regime change, (2) the suburbanization or disurbanization of the 1990s, and (3) demographic decline.

1. Deindustrialisation set in immediately after the change in regime, affecting practically all sectors of the industry and with dire consequences for the economic basis of East German towns and cities. Seventy percent of all job losses were due to the collapse of the industry ([9], p. 4). Thus many industrial and commercial sites fell vacant, especially in the late nineteenth-century urban extensions. An estimated 3–4% or more of land in urban areas, and up to 5% in industrial cities lies vacant

(own estimates on the basis of data on Leipzig), and will probably remain unused in the future. Completely new dimensions in brownfield land in cities are being dealt with here – a process that will continue with the advance of urban redevelopment.

2. From the early 1990s to the mid-decade, the rapid expansion of the housing supply topped the list of local government priorities. In view of the housing shortage in East Germany and positive population forecasts, both the rehabilitation of old city centers and the construction of new housing were pushed. Housing was built everywhere with the aid of tax relief, write-offs, and government subsidies. Between 1991 and 1999 alone, 773,368 new dwellings were built [10], almost exclusively newly constructed on greenfield sites. This led to parallel shrinkage and growth, stepped up land take, and, finally, a government subsidized housing surplus that now – again with government aid – has to be reduced.
3. Demographic decline in East Germany has been caused by outmigration and natural population development. Between 1989 and 2005, some 1.4 million people moved from East Germany to West Germany; if about 500,000 foreigners had not arrived, the migration loss would have been even greater [11]. In addition, there was a natural decline in the population of some 600,000 owing to the massive fall in the birth rate from 1990 ([11], p. 12). Over this period, the total population of East Germany fell by 11.7%. Further decline can be expected owing to demographic change. If the trend in East Germany persists, the population will have halved by 2050. More and more towns and cities, not only in East Germany but also in the western states, are expected to experience stagnation or shrinkage [12].

Owing to demographic developments and outmigration, as well as developments on the property and housing markets, some one million dwellings had fallen vacant by the end of the 1990s. But these vacancies were only one element in the shrinkage problem, which must be understood as a many-facetted upheaval involving economic, social, and cultural factors ([7], p. 58ff.). The many dimensions of this upheaval are beginning to emerge in outline. East Germany has embarked on a specific path in the development of settlement structures which finds little to compare with in West Germany. Some authors have described it as a "disurbanization process" (intra-regional deconcentration of the population in an overall context of demographic decline) [13]. Since shrinkage can be expected to continue in the long term, "reasonable strategies for a retreat from extensive development" are called for [14]. Cities already have to cope with the loss of functions.

The Joint Program of the German Federal and State Governments: "Urban Redevelopment East"

In response to housing vacancies, the federal and state governments set up an expert commission in the late 1990s on "Housing Structural Change in the New States," on whose recommendation the federal government launched the "Urban Redevelopment East" program in 2002 [15]. The scheme was endowed with some €2.7 billion. By 2010, about 350,000 of the circa one million surplus dwellings were to be demolished. The demolition program is currently being implemented almost throughout East Germany. About 350 larger local authorities are now integrated in the program covering about 650 development areas, approximately three quarters of all East German towns and cities with populations of over 10,000 [6]. Most communities receiving support have a vacancy rate of about 10–15%, some even 20%. So far about 220,000 dwellings have been demolished (status end of 2009), reducing the vacancy rate to some 13%. Meanwhile, the demolition program is no longer limited to cautious downsizing: in many cities entire neighborhoods are being razed ([6], p. 11). Redevelopment has so far focused on large housing estates on the urban fringe. Some 40% of development areas are characterized by prefabricated high-rise housing from GDR times. Only one quarter have older housing stock dating from before 1948.

"Urban Redevelopment East" is clearly conceived as a consolidation program for the local housing market, but also pursues ambitious urban development objectives. Support is mainly provided for the demolition of housing, but the remaining stock, infrastructure, and the residential environs are to be upgraded, which includes the provision of new, attractive green structures. The aim is an integrated procedure, linking housing industry problems with urban development aspects. With an eye to ensuring the sustainability of the city as a whole, planned demolitions are to be embedded in urban structures and the neighborhoods involved are to be upgraded at the same time [16]. To ensure that downsizing, redevelopment, and upgrading works are coordinated and that demolition is adapted to the given urban structure, funding is made contingent on the elaboration of integrated urban development plans. Their purpose is "to coordinate the individual measures of urban redevelopment and combine them into a sustainable, meaningful whole" [17] and hence to improve urban amenity. The "Urban Redevelopment East" program thus sets high standards – also for the creation and design of open spaces – which, however, both funding policy and local sectoral authorities have since substantially lowered. The thrust is now clearly toward rapid consolidation of the housing market. Funding for the after-use or conversion of cleared demolition sites are now scarcely available ([16], p. 758); in only one third of cases are upgrading measures undertaken, mostly planting. It is increasingly apparent that downsizing on the "onion-ring principle" from the periphery inward, as preferred by most local authorities, faces considerable difficulties in implementation. Urban redevelopment measures are now almost impossible to embed in an urban development concept, and in many cases they lead to the perforation of the urban structure. As a result, many isolated open spaces and vacant sites of varying sizes are created in the urban fabric. Perhaps for this reason every second local authority regards coping with previously developed land in central and significant locations as a serious problem [18].

In sum, the strategy of controlled shrinkage adopted by many cities has already come up against its limits, since it takes no account of these new needs but continues to be pursued for lack of feasible alternatives. Coping with existing and new brownfield land cleared in the course of urban redevelopment is proving to be a growing problem for which, as it has been seen, the program no longer provides anything like adequate funding.

The Demands Made of the New Open Spaces

The permanent rezoning of residential and industrial land, as well as infrastructure land in such dimensions, is a new urban development task. Initially, traditional demands are made of the new open spaces; they are to serve recreational purposes, for instance, in the form of small parks, green spaces, or playgrounds, and generally contribute to improving residential amenity. Ecological demands are formulated, for example, that habitat networks or green corridors should be created, thus contributing to nature conservation in the city.

Furthermore, new demands are advanced, notably that the new open spaces should help enhance the image of the locality and contribute to the positive presentation of the shrinkage process and its consequences. What is accordingly envisioned is not isolated, planted plots: notions of a "new urban landscape" predominate in which the new open space elements are interlinked ([19], pp 645ff.). The hope is that this will not only improve residential amenity but encourage demand and investment, thus upgrading entire neighborhoods. The new open spaces are hence expected to help stabilize residential areas and counteract vacancies, thus maintaining urban and sociospatial structures. Open space systems are to provide a solid framework for the maintenance of urban structural contexts ([20], p. 737ff.), help integrate peripheral settlements into the surrounding landscape, and to improve and create recreational and locational amenities in inner cities ([6], p. 23; [21]). One particular goal is to establish green corridors that serve both recreational and nature conservation purposes.

The urban redevelopment program treats the creation of green spaces primarily as an element in design upgrading; seldom are ecological or nature conservation goals in focus. Apart from municipal demands for improved residential amenity and better quality of life for local residents, the call for active participation by the public plays a steadily growing role. Top-down urban development is longer judged sufficient: the committed involvement of residents and private actors is also needed. This development also means that more is expected from the open spaces cleared during redevelopment.

In the course of urban redevelopment, neighborhoods, cities, and entire regions set their hopes in the new open spaces as "identity-forming elements" for "when buildings are demolished and entire neighbourhoods downsized, the only remaining key factor in urban development is open space" [22].

What is more, the uses to which open spaces are put change with population decline, aging, diversification, and individualization. The focus shifts increasingly to specific user groups: the elderly, youth, singles, families, women and men, Germans, and immigrants ([22], p. 7). The question is whether the new, differentiated demands can really be met by traditional amenities. They are replaced by uses not typical of the city, with open spaces being understood as creative spaces. They include experience, art, and nature areas such as wild gardens, farmland, event venues, etc. The new open spaces are particularly suitable for social intercourse, offering opportunities for a highly varied urban stage set by the population. Security in such areas plays a major role, and problems can be caused by informal use, for example, as rubbish tips, dog runs, drug trafficking locales, or camp sites for the homeless.

Strategies and Tools for Open Space Development

The current after-uses for previously developed sites range from (complete) clearance or clearance with simple planting or afforestation without precisely defined use requirements, to the layout of permanent green areas (parks, green belts, sport grounds, playgrounds, and other amenities). The *renaturation* (see our definition of the term within the glossary) of such areas is increasingly envisaged for the urban fringe. For some years now, new strategies have been tested, especially in East German cities, experimenting with interim uses in the form of temporary greening (recreation, events, nature conservation), but also with unconventional solutions for permanent green spaces, such as the layout of compensatory areas, downzoning to farmland and urban forest, and urban wilderness. Support is given for the renaturation of land no longer used for building purposes by both the Federal Spatial Planning Act [23] and the Federal Nature Conservation Act [24]. Section 2 (2) (8) of the Federal Spatial Planning Act, listing the principles of spatial planning, lays down that "if land is no longer used on a permanent basis, the productivity of the soil shall be maintained or restored." Section 2 (1) (11) of the Federal Nature Conservation Act prescribes that "Sealed surfaces which are no longer required shall be renatured or, where desealing is not possible or excessively expensive, they shall be left to natural development." In addition, the "National Strategy on Biological Diversity" adopted by the federal government on November 7, 2007, explicitly calls for more greenery in cities [25].

The examples of current and new subsequent uses of urban brownfield sites and their urban development, aesthetic, and ecological value are discussed below.

(Complete) Clearance of Redundant Sites

The consequences of the abandonment of large industrial areas, especially from the early to mid-1990s, have still not always been satisfactorily overcome. In many cases it was sought to revitalize areas through the massively subsidized demolition of buildings and complete clearance of sites, which preparatory land-use plans continued to register as industrial land. Where land could not be successfully marketed or only partially put to new use, unplanned reintegration of the area into the surrounding countryside was often the result, especially on the urban fringe. An undisturbed succession of vegetation thus took over large areas. Although interesting from an ecological point of view, this development met with a very mixed reception among nature conservationists owing the preponderance of ubiquitous species. Aesthetic aspects also gave cause for criticism, and acceptance among the local urban population was often lacking. Such derelict areas provoked anxiety, recalling the decline of entire industries and the associated loss of jobs ([26], p. 79) (Fig. 1).

Simple Clearance

Many downsizing projects funded by the "Urban Redevelopment East" program have already proved problematic, since they leave behind them nothing but simple, often dreary and derelict open spaces for whose maintenance no one accepts responsibility. Many local authorities have demolished or downsized single buildings within existing settlements (prefabricated housing estates, *Gründerzeit* neighborhoods), where, although the buildings have been removed, the technical infrastructure is left in place and sealed and streets retained. Vacant land is usually planted with lawn, and sometimes with a few shrubs or trees. As a rule, these areas are still zoned in the preparatory land-use plan as residential. In some redeveloped areas, especially prefabricated housing

Urban Redevelopment and Quality of Open Spaces. Figure 1
Abandoned land with undisturbed succession on a former industrial zone along the River Elbe in Heidenau (Germany) (Photo: M. Arendt)

estates, vast land-use gaps have now opened up in the once closed structure of the city. Attempts to create extensive green corridors are often in vain; clearance sites tend to be scattered throughout the community. Their ecological value is thus low and their recreation value limited (Figs. 2 and 3).

Development of Permanent Green Spaces

A number of brownfield sites have, however, also been permanently converted into green spaces. Larger brownfield or clearance sites are linked up to form green corridors in the hope of improving social and ecological qualities, and, particularly on the urban outskirts, establishing a transition to the landscape. It is hoped that improving the quality of life and enhancing the image of the locality will help prevent urban sprawl [27]. One successful example of this strategy is the Leipzig-Grünau green corridor (planning and implementation 1993–1996), where the abandoned route of a planned road bordering on rural areas offered favorable conditions for creating a green belt. After demolition of the prefabricated housing, new recreational amenities and green spaces with native trees and shrubs were created in the area, which had been short on greenery and open spaces. Local residents and institutions were involved in planning and design [28]. Such green spaces are generally of great value for recreational uses and, if well designed, can contribute to the ecological upgrading of the neighborhood or of the entire urban territory. Sustained conservation and maintenance can prove problematic, and more and more reliance is put on participation by local residents (Figs. 4 and 5).

Interim Use as Temporary Green Space

Ownership structures can make it difficult for municipal programs to reactivate smaller gap sites scattered throughout the city. Private property owners are wary of the legal repercussions of "official," even temporary, use of their plots and fear for the value of their building land. In order to induce landowners to tackle their vacancy problems, the "authorization agreement" has been developed [29, 30], a tool that provides for the meaningful, temporary public use of private brownfield sites without affecting existing building rights. A contract is concluded between the municipality and the property owner under which the owner makes unused sites available for concrete public uses (simple green areas, playgrounds, neighborhood gardens).

Urban Redevelopment and Quality of Open Spaces. Figure 2
Demolition of a prefabricated housing estate in Dresden-Prohlis (Germany) (Photo: R. Bendner)

In compensation, the municipality offers to pay for design and layout and limited maintenance and provides relief from property tax. Owners have accordingly been more willing to make land temporarily available for a wide range of uses, providing more opportunities for individually designed life spaces [29, 30]. Leipzig has pioneered the temporary use of open spaces under authorization agreements. The municipality has pursued a central objective: "more greenery, less density." The "Guidelines for Urban Renewal" [31] calls for more and better green areas and open spaces. Under authorization agreements, Leipzig has so far managed to develop some 140,000 m^2 of new green areas and open spaces ([29], p. 46), covering a wide range of interim uses. Most temporary green space uses focus on recreation. Depending on how these areas are designed and used, they can also be of incidental and targeted value in attaining urban-ecological goals and offer opportunities for nature conservation in the city (Fig. 6).

Use as Compensatory Areas

The use of inner-city brownfield sites for ecological compensation purposes gives local authorities a valuable opportunity to assert the interests of nature conservation in urban life spaces. For they provide debt-strapped municipalities with a possibility to use the duty imposed by Section 1a (3) of the Federal Building Code to mitigate the impact of development on nature specifically for urban-ecological measures, hence improving quality of life for residents [32]. However, difficult ownership structures and often high preliminary financing costs mean that hardly any suitable sites are available. Ecological upgrading mostly involves de-sealing and planting works. However, the extent to which nature conservation areas can be used by the urban population is problematic. In order to steer impact mitigation compensatory measures into the inner cities, a number of municipalities have formed land pools that include previously developed land. In Leipzig, for example, the city council decided that 50% of compensatory measures under the environmental impact mitigation rules were to involve inner-city brownfield sites (information from the Leipzig Office of the Environment). There is now an intermunicipal compensatory land pool which included most of the land that comes into question. However, as in other cities, it is difficult to find areas for permanent planting in Leipzig.

Urban Redevelopment and Quality of Open Spaces. Figure 3
Simply green former housing area with lawn, few shrubs, and trees in Dresden-Prohlis (Germany) (Photo: R. Bendner)

Permanent Downzoning to Farmland or Forest

Urban and peri-urban agriculture has a long tradition [33]. Regardless of the type and intensity of farming, agricultural areas also provide city dwellers with a wide range of recreational and other amenities [34]. The discussion on the greater use of renewable energies and the growing demand for biomass production can be an economically attractive after-use option for clearance sites in the city. An ongoing Experimental Housing and Urban Development study is examining the use of urban open spaces for renewable energy [35]. Examples of agricultural uses are the short rotation plantations in Halle-Neustadt and the Green Bow in Leipzig-Paunsdorf, the layout of which took account of nature conservation aspects and recreational needs. The types of farming feasible on previously developed urban land will depend on the size of the areas, their location in the urban structure, and on locational prerequisites (e.g., soil quality), but not least on what actors can be found to manage them.

A frequently envisaged category of after-use in renaturation projects is forest or woodland. Forest does not necessarily require the reallocation of holdings, and ensures secure, long-term management, generally by the forest authorities [36]. In contrast to use as conventional green spaces, managing land under the terms of the Forests Act involves much lower investment and maintenance costs, less stringent traffic safety obligations than for the more usual urban open spaces (problem of liability), much lower land values, but also new use options, since public access is maintained. In keeping with the principle of downsizing from the periphery inward, conversion into forest is envisaged primarily on the urban outskirts, with the aim of establishing interconnectivity with the surrounding countryside [37, 38]. In Schwedt "Am Waldrand," for example, the afforestation of clearance sites is planned; in Weißwasser-Süd forest-like mixed plantations have been established, which after 4 years of development care are to be transferred to the forestry authorities. The "Waldstadt" in Halle-Silberhöhe is being laid out on the periphery of the large housing estate, bordering on an extensive young-stand, near-natural deciduous forest [36]. Woodland is used in the inner-city to cover gap sites, maintaining the illusion of density and compactness (e.g., "Dunkler Wald" in Leipzig). Such forested areas attain spatial significance only after a relatively long period, and only then do they correspond to the accustomed image, which can initially lead to problems of public acceptance (Figs. 7 and 8).

Experiment "Wilderness in the City"

In many cases, however, the development of brownfield sites proceeds unsystematically. Depending on how long a vacant plot remains undisturbed or on the way in which it is used, different stages of vegetation development with the associated animal species will predominate. This often results in ecologically valuable habitat mosaics [39–41], which can be precious

Urban Redevelopment and Quality of Open Spaces. Figure 4
New designed green spaces in Leipzig-Grünau (Photo: Municipality of Leipzig)

Urban Redevelopment and Quality of Open Spaces. Figure 5
Public allotments in the Lehne-Voigt-Park in Leipzig (Photo: J. Mathey)

Urban Redevelopment and Quality of Open Spaces. Figure 6
Temporary use of former brownfield as green spaces in the east of Leipzig (Photo: J. Mathey)

Urban Redevelopment and Quality of Open Spaces. Figure 7
Farmland combined with nature conservation on a former military area in Leipzig-Paunsdorf (Photo: Municipality of Leipzig)

Urban Redevelopment and Quality of Open Spaces. Figure 8
"Dark Forest" on a former brownfield in Leipzig (Photo: I. Hartmann)

recreation areas and offer opportunities to experience nature [42]. The question of wilderness in the city is much discussed in the debate on urban redevelopment. This is, however, to be understood not so much as a "free succession" of vegetation with land being completely left to its own devices but as a "regulated succession," a mix of planned, partly cultivated, and "wild" areas [43]. The overgrowth of vacant sites is accepted only if it remains in the prescribed limits and fits into the pattern of new open spaces [44]. "Orderly succession" constitutes a many-facetted habitat mosaic that also exhibits a certain order. This new aesthetic is more acceptable than impenetrable wilderness. Moreover, in comparison with conventional green spaces, considerable savings can be made on layout and maintenance. In contrast to the substantial attention that this subject attracts among the public and experts, it has so far played hardly any role at all in urban redevelopment, and there are very few examples of projects. On a former military site in Dresden-Nickern, a sort of "ruderal park" has been developed, retaining existing spontaneous vegetation, which includes wilderness and natural succession. This ruderal park is accepted and well used by the residents, however, often the development value and amenity quality of such areas is criticized and public acceptance is low ([26], p. 73f.; [45]) (Fig. 9).

Conclusion: New Open Space Qualities Through Urban Redevelopment?

Urban redevelopment has opened up a new field of experimentation and opportunity in the design and use of inner-city open spaces. The new possibilities and opportunities face a complex of obstacles, primarily financial but also legal in nature. They cannot be overcome by traditional strategies: new forms of cooperation are needed. This is also true of coping with the changing demands made on the use of open spaces. Overall, a change of awareness is required, a shift from growth toward a novel combination of growth and shrinkage. Approaches directed toward a subdivided or fragmented urban structure would appear to be more suitable in handling the new open spaces [46].

The advantages offered by "new greenery" such as improved open space amenity, the concomitant ecological upgrading, or the attention paid to the interests of nature conservation are counterbalanced by a number of disadvantages. One is the fragmentation of the physical urban fabric, the perforation of the city, and, not seldom, the limited use capability of the new open spaces. What is more, these new open spaces are often still encumbered by the remains of urban infrastructure. Sometimes they have a derelict aspect, which contributes to stigmatization. Although urban redevelopment produces many new open and green spaces, it leads to a loss of design quality and amenity when measured against existing standards and the associated demands made of urban open space. The importance of open space planning in shrinking cities is therefore increasing; it is becoming one of the "most important tools of urban development" ([19], p. 648).

In the course of urban redevelopment, new open spaces are also expected to perform urban development tasks and functions. It is questionable whether they are suitable, for the new open space qualities envisioned by integrated urban development concepts do not emerge at once. To begin with, much takes the appearance of isolated pieces of a puzzle or tiles in a mosaic without recognizable outline, or is provisional and transitory in nature. For example, it is not yet clear what is to become of the experiments with vegetation succession. Many experimental projects – including forms of extensive maintenance, wilderness, and succession – are experienced as impoverishment [47]. In the short

Urban Redevelopment and Quality of Open Spaces. Figure 9
"Orderly Succession" on a former military area in Dresden-Nickern (Photo: R. Bendner)

and medium term, many cities will have to live with open spaces that attain their aesthetic qualities only gradually ([26], p. 74). Since planning practice largely stands by the accustomed types of open space [46, 48], the permanent conversion of redundant building land into urban green spaces of conventional design and function (e.g., parks, playgrounds and recreation facilities, and allotment gardens) is, despite financial restrictions, likely to remain the most frequent after-use for clearance sites in the inner-city and residential areas. However, as budgets shrink, urban parks departments are already scarcely able to maintain their green areas, let alone take on additional cleared sites. In the future, new types of open spaces are therefore likely to be established alongside the accustomed ones, especially areas that allow stronger forms of succession. Thus a growing number of cities undertaking urban redevelopment can be expected to embark on the adventure of succession ([49], p. 12), but they will by no means be overgrown as a result. One outcome of urban redevelopment in the cities concerned will be a more self-stabilizing nature. In view of the far-reaching transformations that redevelopment cause in the cityscape, however, these changes can be regarded as secondary. In sum, urban redevelopment and more greenery will not directly enhance quality in the conventional sense. The population will have to get used to a new quality of the city and its new open spaces. And the decisive innovation will perhaps be a shift in perspective that allows open spaces to be seen with new eyes.

Outlook: Future Directions

As pointed out (in the conclusions) above, the reintegration of brownfields into the urban fabric by developing green and open spaces (renaturation) is a big challenge, which in future times will become of more and more importance. There is a chance to reconstruct the urban structure (urban fabric) and give cities new faces, but new overall strategies are necessary and a lot of obstacles have to be overcome. In the planning, practice cities have to face a lot of implementation problems such as (1) availability of brownfields (sites not in the ownership of the community), (2) financing of measurements and maintenance, (3) missing cooperation of different city departments, (4) meeting the needs of residents (public relation, participation), (5) considering legal and strategic requirements, and (6) necessitating the profit gain out of the sites. Finding solutions demands for interdisciplinary (research) approaches, where ecological, social, economical, and planning aspects are taken into consideration to develop overall strategies (and concepts) that lead to a “new urban landscape” with valuable, usable, and accepted green and open spaces in a sustainable urban structure.

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Glossary Terms

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