Runming Yao *Editor*

# Design and Management of Sustainable Built Environments

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# Foreword

Today sustainability is a word that pervades architecture and building engineering whether planning, designing, or managing a building or city. In this book there is a bias toward buildings but six of the twenty chapters deal with the urban context. There is a vital need to bring planning, design, and management closer together and this book goes some way toward achieving this.

The approach has been to compile a mixture of chapters which cross and interface disciplines devoted to strategic and tactical issues that are needed to fulfill the principal objective of being sustainable at all stages of the planning, design, and management processes. Each chapter has a Learning Scope which will benefit students who are reading and researching these topics for Master's degree programs in architecture and environmental engineering. The distinguished band of international authors led by Dr. Runming Yao at the University of Reading comes from several universities with some contributions from the industry.

The book emphasizes integration and interdisciplinarity with the principal intention of showing how research can help to solve worldwide problems in the general area of the sustainable built environment in the hope that readers will be stimulated to think more creatively about these issues.

New and amended regulations to cover energy and carbon dioxide emissions are cascading over us continually. One needs to surface and breathe fresh air to avoid being suffocated by so many rules, codes, standards, and regulations. Dealing with them, and remembering that they are a minimum threshold only and do not guarantee a really successful building in the eyes of the occupants, dulls the mind, and freezes creative thought as does the never-ending stream of e-mails many of us receive daily today. So this book is a welcome stimulant for some lateral thinking.

Fragmentation of any kind does not lead to good architecture. Planning, designing, constructing, and managing a building have many things in common with evolving a city with its complex of infrastructures and buildings. Whether the nineteenth century professional institutions have helped in fragmenting all the knowledge and actions an architect-engineer like the first century Vitruvius saw as a whole is debateable. This book traverses the urban and building interior landscapes confidently as demonstrated in the chapters which discuss urban issues and others on modeling analysis techniques. We need to think and work together from whatever discipline we emanate.

The human element should be at the center of our thinking whether it is the impact of occupants' behavior on energy patterns of consumption or briefing the internal environment necessary for wellbeing. Two chapters cover these aspects remembering that the sustainable built environment must promote health and quality of life. In addition, to sustain building performance effective facilities management is vital to ensure care of the systems and hence the people.

There are few books that cover the internal and external environments ranging from masterplanning to facilities management. At a time when new specialists in sustainability are emerging this book is timely and will make a valuable reference for students and professionals alike.

Reading, UK, May 2012

Derek Clements-Croome
Professor Emeritus in Architectural Engineering
The University of Reading

# Preface

The United Nations Intergovernmental Panel on Climate Change (IPCC) makes it clear that climate change is due to human activities and it recognizes buildings as a distinct sector among the seven analyzed in its 2007 Fourth Assessment Report. Global concerns have escalated regarding carbon emissions and sustainability in the built environment. The built environment is a human-made setting to accommodate human activities, including building, and transport, which covers an interdisciplinary field addressing design, construction, operation, and management. Specifically, sustainable buildings are expected to achieve high performance throughout the life cycle of siting, design, construction, operation, maintenance, and demolition in the following areas:

- energy and resource efficiency;
- cost-effectiveness;
- minimization of emissions that negatively impact global warming, indoor air quality, and acid rain;
- minimization of waste discharges; and
- maximization of fulfilling the requirements of occupants' health and wellbeing.

Professionals in the built environment sector, such as urban planners, architects, building scientists, engineers, facilities managers, performance assessors, and policy makers, will play a significant role in delivering a sustainable built environment. Delivering a sustainable built environment requires therefore an integrated approach and so it is essential for built environment professionals to have interdisciplinary knowledge in building design and management. Building and urban designers need to have a good understanding of the planning, design, and management of buildings in terms of low carbon and energy efficiency. There are a limited number of traditional engineers who know how to design environmental systems (services engineer) in great detail, yet, there is still a very large market for technologists with multi-disciplinary skills who are able to identify the need for, envision, and manage the deployment of a wide range of sustainable technologies, both passive (architectural) and active (engineering system), and select the appropriate approach. Employers seek applicants with skills in analysis, decision making/assessment, computer simulation, and project implementation. An integrated approach is expected in practice, which encourages built environment professionals to think 'out of the box' and learn to analyze real problems using the most relevant approach, irrespective of discipline.

The *Design and Management of Sustainable Built Environments* book aims to produce readers capable of applying fundamental scientific research to solve real-world problems in the general area of sustainability in the built environment. The book contains twenty chapters covering climate change and sustainability, urban design and assessment (planning, travel systems, urban environment), urban management (drainage and waste), buildings (indoor environment, architectural design, and renewable energy), simulation techniques (energy and airflow), management (end-user behavior, facilities, and information), assessment (materials and tools), procurement, and cases studies (BRE Science Park).

Chapters 1 and 2 present general global issues of climate change and sustainability in the built environment. Chapter 1 illustrates that applying the concepts of sustainability to the urban environment (buildings, infrastructure, transport) raises some key issues for tackling climate change, resource depletion, and energy supply. Buildings, and the way we operate them, play a vital role in tackling global greenhouse gas emissions. Holistic thinking and an integrated approach in delivering a sustainable built environment is highlighted. Chapter 2 demonstrates the important role that buildings (their services and appliances) and building energy policies play in this area. Substantial investment is required to implement such policies, much of which will earn a good return.

Chapters 3 and 4 discuss urban planning and transport. Chapter 3 addresses the importance of using modeling techniques at the early stage for strategic masterplanning of a new development and a retrofit program. A general framework for sustainable urban-scale masterplanning is introduced. This chapter also addresses the needs for the development of a more holistic and pragmatic view of how the built environment performs. Urban planning tools will assist to achieve a higher level of sustainability in the built environment. The chapter, in particular, introduces how people plan, design, and use the tool. Chapter 4 discusses micro-circulation, which is an emerging and challenging area which relates to changing travel behavior in the quest for urban sustainability. The chapter outlines the main drivers for travel behavior and choices, the workings of the transport system, and its interaction with urban land use. It also covers the new approach to managing urban traffic to maximize economic, social, and environmental benefits.

Chapters 5 and 6 present topics related to urban microclimates including thermal and acoustic issues. Chapter 5 discusses urban microclimates and urban heat island, as well as the interrelationship of urban design (urban forms and textures) with energy consumption and urban thermal comfort. It introduces models that can be used to analyze microclimates for a careful and considered approach in planning sustainable cities. Chapter 6 discusses urban acoustics, focusing on urban noise evaluation and mitigation. Various prediction and simulation methods for sound propagation in micro-scale urban areas, as well as techniques for large-scale urban noise-mapping, are presented.

Chapters 7 and 8 discuss urban drainage and waste management. The growing demand for housing and commercial developments in the twenty-first century, as well as the environmental pressure caused by climate change, has increased the focus on sustainable urban drainage systems (SUDS). Chapter 7 discusses the SUDS concept which is an integrated approach to surface water management. It takes into consideration quality, quantity, and amenity aspects to provide a more pleasant habitat for people as well as increasing the biodiversity value of the local environment. Chapter 8 discusses the main issues in urban waste management. It points out that population increases, land use pressures, technical, and socioeconomic influences have become inextricably interwoven and how ensuring a safe means of dealing with humanity's waste becomes more challenging.

Sustainable building design needs to consider healthy indoor environments, minimizing energy for heating, cooling and lighting, and maximizing the utilization of renewable energy. Chapter 9 considers how people respond to the physical environment and how that is used in the design of indoor environments. It considers environmental components such as thermal, acoustic, visual, air quality, and vibration and their interaction and integration. Chapter 10 introduces the concept of passive building design and its relevant strategies, including passive solar heating, shading, natural ventilation, daylighting, and thermal mass, in order to minimize heating and cooling load as well as energy consumption for artificial lighting. Chapter 11 discusses the growing importance of integrating Renewable Energy Technologies (RETs) into buildings, the range of technologies currently available and what to consider during technology selection processes in order to minimize carbon emissions from burning fossil fuels. The chapter draws to a close by highlighting the issues concerning system design and the need for careful integration and management of RETs once installed; and for homeowners and operators to understand the characteristics of the technology in their building.

Computer simulation tools play a significant role in sustainable building design because, as the modern built environment design (building and systems) becomes more complex, it requires tools to assist in the design process. Chapter 12 gives an overview of the primary benefits and users of simulation programs, the role of simulation in the construction process and examines the validity and interpretation of simulation results. Chapter 13 focuses particularly on the Computational Fluid Dynamics (CFD) simulation method used for optimization and performance assessment of technologies and solutions for sustainable building design and its application through a series of cases studies.

People and building performance are intimately linked. A better understanding of occupants' interaction with the indoor environment is essential to building energy and facilities management. Chapter 14 focuses on the issue of occupant behavior; principally, its impact, and the influence of building performance on them. Chapter 15 explores the discipline of facilities management and the contribution that this emerging profession makes to securing sustainable building performance. The chapter highlights a much greater diversity of opportunities in sustainable building design that extends well into the operational life. Chapter 16 reviews the concepts of modeling information flows and the use of Building

Information Modeling (BIM), describing these techniques and how these aspects of information management can help drive sustainability. An explanation is offered concerning why information management is the key to 'life-cycle' thinking in sustainable building and construction.

Measurement of building performance and sustainability is a key issue in delivering a sustainable built environment. Chapter 17 identifies the means by which construction materials can be evaluated with respect to their sustainability. It identifies the key issues that impact the sustainability of construction materials and the methodologies commonly used to assess them. Chapter 18 focuses on the topics of green building assessment, green building materials, sustainable construction, and operation. Commonly used assessment tools such as BRE Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and others are introduced.

Chapter 19 discusses sustainable procurement which is one of the areas to have naturally emerged from the overall sustainable development agenda. It aims to ensure that current use of resources does not compromise the ability of future generations to meet their own needs.

Chapter 20 is a best-practice exemplar—the BRE Innovation Park which features a number of demonstration buildings that have been built to the UK Government's Code for Sustainable Homes. It showcases the very latest innovative methods of construction, and cutting edge technology for sustainable buildings.

In summary, the *Design and Management of Sustainable Built Environments* is the result of cooperation and dedication of individual chapter authors. We hope readers will benefit from gaining a broad interdisciplinary knowledge of design and management in the built environment in the context of sustainability. We believe that the knowledge and insights of our academics and professional colleagues from different institutions and disciplines illuminate a way of delivering sustainable built environment through holistic integrated design and management approaches. Last, but not least, I would like to take this opportunity to thank all the chapter authors for their contribution. I would like to thank David Lim for his assistance in the editorial work.

May 2012

Runming Yao
The University of Reading

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# About the Editor

**Dr. Runming Yao** is a Reader in Energy and the Built Environment; academic lead for the Innovative and Sustainable Technologies (IST) Research Group and Course Director of the postgraduate program 'Design and Management of Sustainable Built Environments' within the School of Construction Management and Engineering at the University of Reading, UK. Prior to joining the University of Reading in 2007, she was a Senior Research Associate in the Department of Architecture at the University of Cambridge where she worked for six years in the field of environmental architectural design. Dr. Yao is a Chartered Engineer; a Fellow of the Chartered Institution of Building Services Engineers (CIBSE); a Fellow of the Chartered Institute of Building (CIOB), a Member of the American Society of Heating Ventilation, Refrigerating and Air-Conditioning Engineers (ASHRAE) and a Fellow of the Higher Education Academy (HEA). Dr. Yao teaches at both postgraduate and undergraduate levels on the topics of architectural and environmental engineering, energy efficient building design, indoor environment and wellbeing, intelligent buildings and energy operation & management. Dr. Yao's research focuses are on energy efficiency; indoor environment and wellbeing; urban microclimates, and occupants' thermal comfort and adaptive behavior. She has completed numerous research projects by a wide variety of resource and published numerous refereed journal articles internationally.

# Contributors

**Andrew Baldwin** has recently retired from his position as Professor of Construction Management at Loughborough University in the UK, and reworked as a visiting Professor of Chongqing University in China. He has extensive academic and construction industry experience. His research has included most aspects of Construction Management including information management within the design and construction process. Following several years' experience in Hong Kong, he has established links in mainland China and in 2011 was appointed as a Distinguished Visiting Professor to Chongqing University.

**Tony Day** is Director of the International Energy Research Centre based at the Tyndall National Institute at University College Cork, Ireland. Prior to that he was Energy Services Director at TEAM (EAA Ltd) and Professor of Energy in the Built Environment at London South Bank University (LSBU). At LSBU he was Director of the Centre for Efficient and Renewable Energy in Buildings. He has over 20 years experience of research, consultancy and teaching of energy efficient buildings and the application of renewable energy technologies. He is a Fellow of the Energy Institute, member of CIBSE, and chair of the UK Solar Energy Society.

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**Chris Gaze** is Technical Director of Innovation and Productivity, BRE. He has a background in manufacturing having worked in engineering before joining the Warwick Manufacturing Group to specialize in house building as a Manufacturing Process. Since then he has been involved in a number of projects involving the setup and improvement of off-site manufacturing facilities before joining BRE, where he now works extensively in helping companies with new developments such as the code for sustainable Homes and Eco-towns.

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**Will Hughes** is a Professor of Construction Management and Economics at the School of Construction Management and Engineering, University of Reading and Editor-in-Chief of *Construction Management and Economics*. He carries out research into construction procurement and project organization. This includes the control and management of building contracts, management of design, professional issues, analysis of organizational structure, and the analysis of procurement systems. The focus is on the commercial processes of structuring, negotiating, recording, and enforcing business deals in construction.

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**Phil Jones** is a Chair Professor of Architectural Science and Director of Architectural Science Research at the Welsh School of Architecture, Cardiff University. Since 2003 he has held the position of Head of School. His research activities encompass a range of subjects in the field of energy use, environmental design, and sustainability in the built environment and he has published extensively in the field and carried out numerous funded research projects in UK, Europe, Malaysia, Middle East, and China. He chairs the Wales Low Carbon Research Institute (LCRI), a consortium of five universities, working with the government and industry to promote the low carbon agenda in Wales.

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**Ken Parsons** is a Pro Vice Chancellor for Research and Professor of Environmental Ergonomics at Loughborough University. He is Chair of BSI; CEN; and ISO committees concerned with producing standards for people in physical environments. He received the Ralph G Nevins award from the American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for contributions to Biomedical Engineering and Thermal comfort. He has been a WHO advisor on heat waves and health and he is Co-Editor in Chief of the Journal *Applied Ergonomics* and a visiting Professor to Chongqing University in China.

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**Sam Laryea** is a Senior Lecturer in the School of Construction Economics and Management at University of the Witwatersrand in South Africa. He is a graduate of the University of Reading (Ph.D.) and Kwame Nkrumah University of Science and Technology, Kumasi (B.Sc.). He is an author of over thirty research publications relating to construction procurement and project risk management. Sam is a coorganizer for the West Africa Built Environment Research (WABER) Conference.

**Andrew Miller** has recently retired from the University of Brighton where he was Professor of Building Sustainability. His research has evolved around the environmental life cycle of buildings with a focus on the efficient use of energy in buildings, the use of renewable energy and the embodied energy within the building materials. Andrew is an active member of the World Renewable Energy Network (WREN) and is a regular presenter on sustainable materials at their international seminars. He is an Adjunct Professor at Curtin University in Perth, Australia where he is collaborating in a research project on sustainable refurbishment.

**Alan Short** is a Professor of Architecture at the Department of Architecture, University of Cambridge. His research group develops passive and hybrid low-energy design strategies for non-domestic building types in different climates, both new-build and rebuild, projecting their future performance against current climate change predictions. Current funded research is investigating the sustainable design of hospitals, arts buildings, and libraries. He won the first 'RIBA President's Award for Outstanding Practice-located Research 2007' and the 'RIBA President's Commendation for Outstanding University-located Research 2009', 'Green Building of the Year Award 1995' and the 'High Architecture Low Energy Award'.

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**Jaya Skandamoorthy** is Director of Enterprise and Innovation, BRE. He is responsible for leading BRE's business growth in innovation and managing the BRE Innovation Park—which has attracted over 60,000 visitors since it was opened by the Deputy Prime Minister in June 2005. His previous role at BRE was head of marketing and business development where he was responsible for identifying key growth markets and developing strategies for delivering an integrated consultancy service and supporting to BRE's strategic growth initiatives.

**Martin Townsend** has a diverse professional background ranging from advising UK Ministers, as a Regulator in his time at the Environment agency, to working on many construction sites. He joined BRE (Global) as Director of BREEAM in 2008 to drive BREEAM forward not just in the UK market, but also internationally.

Martin works closely with the construction industry bringing sustainability issues alive for companies right across Social, Economic, and Environmental agenda.

**Li'ao Wang** is a Professor of Environment Science at Chongqing University. Her research interests include solid waste treatment and management, renewable energy, and environmental impact assessment. She has been an recipient of a number of funding grants from the National Natural Science Foundation of China, the National Key Technology Program. She was awarded the prize of National Advancing Science and Technology Award, the Ministry of Education Award, and the Chongqing Science and Technology Awards. She has published over 100 papers in journals and holds seven patents.

**Chuck Yu** is the Executive Director and President of the International Society of the Built Environment (ISBE), and the Editor-in-Chief of the journal *Indoor and Built Environment*. He has been appointed as a distinguished professor at the School of Human Settlement and Built Environment, Xi'an Jiaotong University in China. He was a technical member of the BSI committee (PRM 72/-) and contributed to the development of CEN TC88 standards for thermal insulating plastic foams. He had also contributed to the validation of the European and International standards for determination of VOC emissions from building materials and indoor air quality.

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# Chapter 1
# Sustainability in the Built Environment

**Runming Yao**

**Abstract** This introductory chapter sets the scene for the book, providing an overview of sustainability in the built environment. With a bias towards buildings and the urban environment, it illustrates the range of issues that impinge upon global carbon reduction and the mechanisms available to help bring about change. Climate change, and its impact on the built environment, is briefly introduced and sustainability in the built environment and associated factors are described. The specific topics relating to sustainable design and management of the built environment, including policy and assessment, planning, energy, water and waste, technology, supply and demand, and occupants' behavior and management have been highlighted. This chapter emphasizes the importance of a systemic approach in delivering a sustainable built environment. *Learning outcomes*: on successful completion of this chapter, readers will be able to: (1) Gain broad knowledge of sustainable built environment, (2) Understand the concept of systemic approach, and (3) Appreciate interdisciplinary aspects of design and management.

**Keywords** Sustainability · Built environment · Building · City · Design · Management

## 1.1 Introduction

Climate change is one of the major challenges the world has faced since the start of the twenty-first century. Greenhouse gas emissions due to the burning of fossil fuel are considered as the main cause of global warming. Approximately 50 % of

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energy consumptions and carbon dioxide ($CO_2$) emissions are from buildings for heating, cooling, and lighting in developed countries. Around 20–30 % is used in transport, while the remainder is used for industrial processing. The development of a sustainable built environment requires a solution which is drawn from complex systems that encompass design and management, the integration of technology and its users and an evaluation of the performance of the whole process. Sustainable development, amongst other issues, requires the rapid and successful uptake of technologies and designs in both new construction and refurbishment. The control and management of the integration of the complex interactions of humans, climates, buildings, and energy systems is also essential within a context of rapidly evolving financial incentives, regulations, and policies which are driving and encouraging changes in environmental engineering. In the past, advanced technologies and methods have been developed in isolation, for example, in urban planning, architectural design, services design, facilities management, and construction. However, it is now necessary to evolve a series of inter-linked systems through genuine interdisciplinary collaboration and dialog. This will support the development of boundary-spanning methodologies that are capable of measuring, monitoring, managing and directing whole system operations, outputs, and impacts. There are two key challenges to the development of such an integrated approach. One is the compartmentation of built-environment professions; such as urban planners, architects, and engineers while the other is the differing perceptions of sustainability of policymakers, built environment professions, industry stakeholders, and end-users. It is important for built environment professionals to overcome these challenges and promote collaborative working between these different constituencies. It is also important to persuade clients that sustainable building design, construction, and operation can save money in terms of energy and water consumptions that can also result in healthier buildings with a consequent price in productivity. This book aims to provide a broad range of knowledge relevant to sustainability in the built environment. Through the content of different chapters, readers will be able to assimilate the range of topics necessary to analyze and synthesis solutions in sustainable built environment design.

## 1.2 Climate Change Impacts

Climate change and global warming will most certainly impact buildings throughout the world (Parry 2007). The latest assessment of the intergovernmental panel on climate change (IPCC), demonstrates that a range of impacts are expected in the future (IPCC 2007a, b). The extent and seriousness of these impacts in the longer term will depend on the extent to which efforts to mitigate greenhouse gas emission are successful (GO-Science 2008). The impacts on the built environment, for example (Dawson 2007) will be:

- Sea-level rise;
- Increased flooding and droughts due to changes in patterns of rainfall, with knock-on effects on drainage systems and water management;
- Increased incidence of heatwaves which can damage infrastructure (e.g., by softening of road blacktop (tarmac)) as well as threatening human health;
- Increased incidence of storms which can damage building and other infrastructure;
- Health impact due to increased heat stress and migration of diseases;
- Changes in demand for goods and services such as more year-round outside activity, and more air conditioning in the summer.

In the GO-Science report, it is stated that these impacts will affect both physical infrastructure of built environment and the lifestyle and wellbeing of the people and communities that live within it (GO-Science 2008). The changes will have implications on the way we live in and operate our buildings. Therefore, built environment needs to change and adapt to these changes in the aspects of: mitigation of greenhouse gas emission, urban and indoor environmental, urban drainage systems, management of waste, eliminate adverse impact on people's health, and wellbeing.

There is a vast array of studies focused on seeking to quantify and predict the impact of our changing climate on the urban environment. For a thorough review of the literature concerning climate change and buildings, readers are directed to de Wilde and Coley (2012). Figure 1.1 shows the mechanisms in which climate change is expected to impact on buildings. It is evident from the 'impact on buildings' column that there will be some profound and devastating consequences in the worst instances. Furthermore, when we look at the 'effects on occupants and key processes', illness, injury, and mortality are startling factors that 'jump out' from the process diagram. In summary, it illustrates the concerns that are currently being raised in politics, industry, and academia regarding this matter.

The two main approaches in this area are *adaptation* and *mitigation*. Adaptation involves designing buildings which respond to the climate change in order to cope. This involves designing buildings with: (1) greater flexibility; (2) intelligent energy management systems; (3) smart appliances; and (4) a view to managing them better. In contrast, mitigation strategies look at reducing energy consumption from the urban environment in the first place. This involves the diffusion of low and zero carbon technologies in buildings that help minimize energy use and thus greenhouse gas emissions.

In a study that looks at balancing adaptation and mitigation in the US and Australia, Hamin and Gurran (2009) note that increasing housing density and the mix of land use is an mitigation strategy, whereas revising infrastructure and capacity is solely an adaptation strategy.

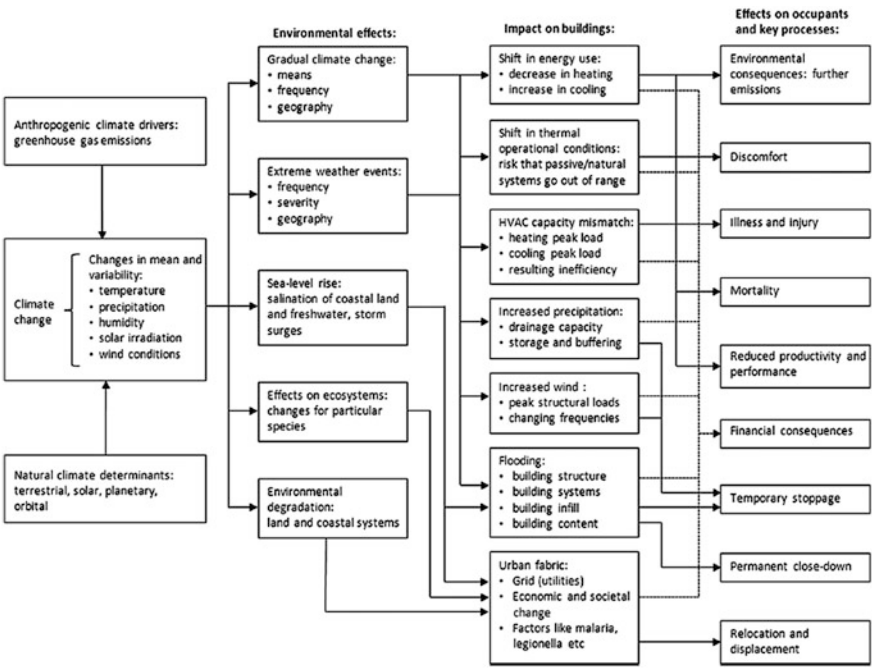


**Fig. 1.1** Schematic overview of the main mechanisms in which climate change impacts on buildings (*source* de Wilde and Coley 2012)

## 1.3 Sustainability

What does *'Sustainability'* really mean and what are the implications in a wider context? The concept of sustainable development had its roots in the idea of a sustainable society (Brown 1981) and in the management of renewable and non-renewable resources. The concept was introduced in the World Conservation Strategy by the international union for the conservation of nature (IUCN 1980). In 1983, The *United Nations General Assembly* passed resolution 38/161 (UN 1983) establishing The world commission on environment and environmental development (WCED). It published a report entitled *Our Common Future* (Bruntland 1987), otherwise known as *The Bruntland Report*. Famously, it coined the three pillared definition of 'sustainability': encompassing economic, environmental, and social factors (Fig. 1.2) with 'sustainable development' at the epicenter.

Moreover, key to the central theme of their definition is the marriage between *environment* and *development*. The two being inextricably linked. That they coexist, a second definition was born: the definition of 'sustainable development'. It reads: *'development thatmeets the needs of the present without compromising the ability of future generations to meet their own needs'* (Bruntland 1987). While

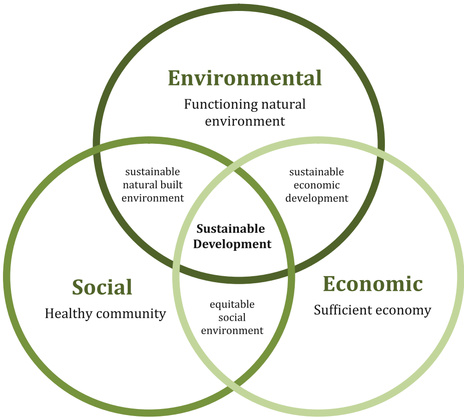


**Fig. 1.2** Triangulated definition of sustainability

politically sensitive, sustainable development is a concept not readily embraced by all governments.

Looking back at a publication in 2001, the UK Department of Trade and Industry's (DTI) Foresight Programme produced a report entitled *Constructing the Future* (DTI 2001). When addressing actions for sustainability, recommendations noted: (1) the promotion of 'smart' buildings and infrastructure; (2) improvements in the health and safety of those employed in the construction industry; (3) enabling supply chain integration; (4) investing in people; (5) improving existing built facilities; (6) exploiting global competitiveness; (7) embracing sustainability; (8) increasing investment returns; and (9) the need to plan ahead. In addition, the report also outlined the changing demands that would impact on the built environment. These included: changing population demographics, knowledge-based working practices and climate change. It also suggested actions based on *whole life thinking* and the use of advanced technology, materials, and processes. In response to this, a UK research consortium composed of academic and industrial partners was initiated: the *design construction and operation of buildings for people* (IDCOP). The need to ask more precise questions raised four key research aims; to better understand: (1) the impact that the use of buildings have on the environment and quality of life of occupants/users; (2) the changing demands being made of existing buildings; (3) the potential for technical/operational developments to improve the performance of the building; and (4) the barriers to implementation. Figure 1.3 shows the research framework they adopted when attempting to look into these issues. The ostensible drivers for change, i.e., product, people, process feature at the heart of the approach, based on the premise that: *'a better understanding of the fundamental relationships between buildings, people and the environment is required if real improvements in the 'sustainable' performance of the urban environment are to be achieved'* (Jones and Clements-Croome 2004).

Reflecting upon the phenomenal economic growth of the BRIC nations (Brazil, Russia, India, China) and the newer set of emerging economies (the CIVETS: Colombia, Indonesia, Vietnam, Egypt, Turkey, and South Africa), energy

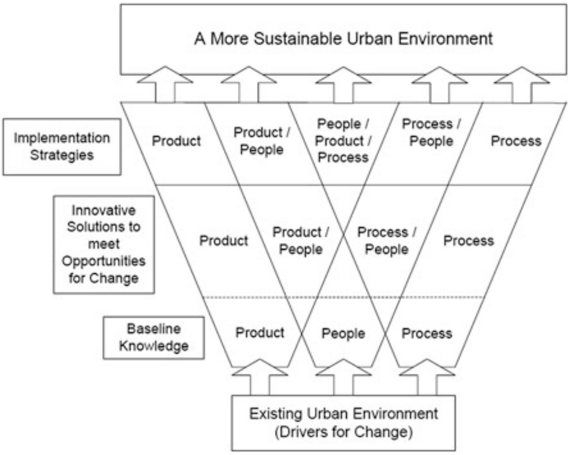


**Fig. 1.3** Interaction between research themes and key drivers (*source* Keith Jones and Derek Clements-Croome 2004)

consumption, carbon emissions and demand for raw materials and fossil fuels will inevitably increase in the short term which is a worrying prospect. China alone is expected to contribute 36 % of global energy growth: a 75 % increase between 2008 and 2035 (IEA 2010). And to fully appreciate the magnitudes involved: China's carbon emissions associated with cement production in 2009 were approximately twice the UK's total carbon emissions for the same year. Interestingly, it is worth noting that most of the world's carbon emissions from a historical perspective, originate from the *developed world*, exacerbated from efforts since the dawn of the industrial revolution.

Observing events from 1950 onward, it could be argued that *population* could be a causal factor for changes in temperature and carbon emissions (UN 2008; IPCC 2007a; Marland et al. 2003). Delving into numbers; since the late nineteenth century world population has quadrupled and energy demand has increased by a factor of 60 (Azapagic and Perdan 2011). The average person today consumes approximately 15 times more energy compared to someone 130 years ago (Mullersteinhagen and Nitsch 2005). World population stands at 7.1 billion in 2012, with growth forecasts placing figures between 8.01 and 8.26 billion by 2025, and 9.15–11.03 billion by 2050 (UN 2008).

Continuing with demographics, household sizes in the UK are decreasing. Between 1961 and 1991 mean household size decreased from 3.01 to 2.48, by 1998 this figure dropped to 2.32 and remained on a stable course until 2002 (ONS 2004). Looking forward, projections place figures in the region of 2.28 by 2011 and 2.13 by 2031 (CLG 2006). Decreasing trends may have roots in social structures and increased disposable income. Nevertheless, it is fair to assume that energy per capita is increasing, characterized by fewer people benefitting from 'shared services' such as communal heating or lighting (Yohanis et al. 2008).

Another demographic phenomenon is *urbanization*. Lured by the romanticism of 'a better life' with higher salaries, or worse, pushed by the absence of farmable

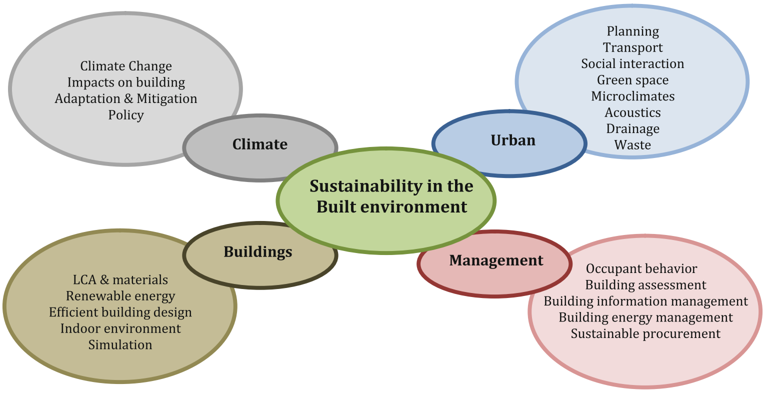


**Fig. 1.4** Sustainability in the built environment: associated factors

climate, people are moving from rural areas to towns and cities on a mass scale. Since 2007, more than half of the world's population now reside in cities. For less developed countries, the intensity of this shift is much greater, with estimates expecting urban populations to nearly double within the next 40 years from about 2.6 to 5.3 billion people (Madlener and Sunak 2011). China's urbanization rate has risen from 23.7 % in 1985, to 36.1 % in 2000, to 45 % in 2007. With a predicted rate of 50 % by 2012 (CURC 2008), a *'substantial pressure on resources and the environment will be experienced'* (Li and Yao 2009). City populations need housing, municipal buildings, and a supporting infrastructure that consume vast quantities of energy, water, and natural resources during construction and operation.

When expanding on the ideas in Fig 1.1, it becomes ever more apparent of the wide ranging issues and concepts that sustainability encompasses. One essential ingredient that consolidates the individual components is *the built environment*. Principally, this includes: (1) climatic factors; (2) general urban issues; (3) buildings design; and (4) the management of buildings. Figure 1.4 shows the holistic connectivity between these themes and an extension of these ideas in diagrammatical form.

The chapters within this book address each of the themes listed in the outermost rings, adding detail and insight through description, examples, and case studies.

## 1.4 Systemic Approach in Built Environment

The successful implementation of a technology, method, or process has been limited by a lack of integration and understanding across various organizational boundaries and between divergent sets of stakeholders. The reframing of technical aspects of energy efficiency requires a holistic framework to include the social and organizational dimensions (Li and Yao 2012). Fundamental research is needed to develop a holistic framework that is capable of evaluating the options involved in a variety of energy management concepts, advances in technologies, the dissemination of energy-saving measures to different stakeholders, local energy generation and distribution planning, and validating what actually happens (measurable, reportable, verifiable) in buildings' energy consumption. The transition to a sustainable built environment requires guidance from complex systems that encompass policy and regulation, the integration of technology and its users, and an evaluation of the performance of the whole process. The built environment is regarded as a complex system including multielements which interact both directly or indirectly (Godfrey 2009; Nicol 2011).

A conceptual systemic framework for a research strategy focussing on the built environment is proposed, illustrated in Fig. 1.5. The concept of a systemic research framework encourages collaborative work among professionals from different disciplines including policy-makers, urban planners, architects, engineers, etc. (Yao 2011).

The key points about the framework are:

- *Integrated whole-life thinking*: Policy, regulatory, benchmarks, and assessment/evaluation mechanisms are needed throughout the whole life of the urban infrastructure and buildings. This means better integration between the planning, design and operation, and management stages. The careful alignment of evolving financial incentives, regulations, and policies, environmental awareness education alongside advances in technology is required to drive and

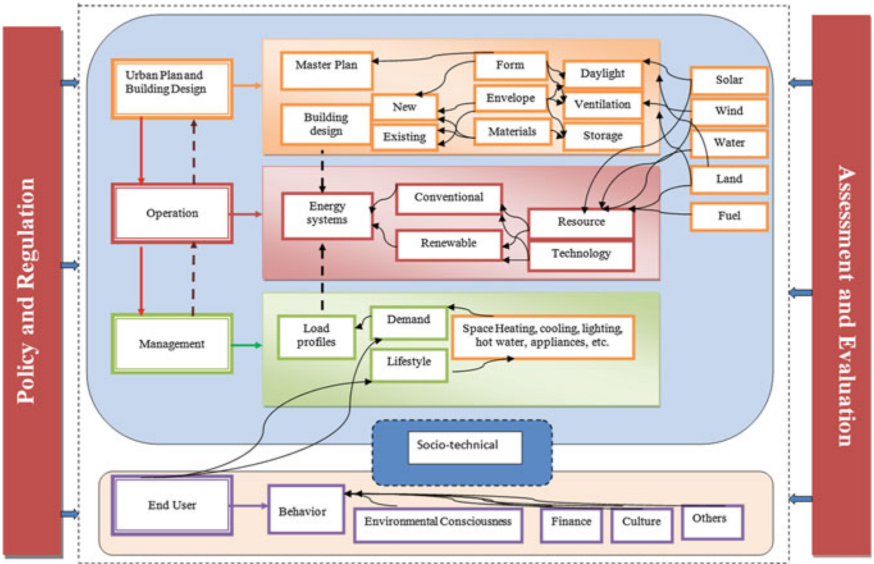


**Fig. 1.5** The integrated approach in built environment research

manage the move toward a low-carbon built environment as well as to avoid pernicious outcomes.

- *Integrated design process*: Traditional sequential processes of passive building design, energy system integration, and operation need to be challenged in order to change their direction and become collaborative processes. Collaborative briefing including planners, architects, engineers, managers, and assessors should be considered at the very early stages of development (cf. Soft Landings, Leaman et al. 2010). Urban built forms, materials, water, and vegetation will have a great impact on energy demand from buildings in terms of usage of passive solar, wind energy, natural ventilation, and daylighting (Salat 2009). An optimum urban plan and building design can significantly reduce the energy burden on energy systems. Renewable energy needs to be carefully integrated into building and built-in energy systems to form a maximum efficiency energy system for buildings. Building materials can play a role of thermal storage in conjunction with the application of solar energy. The growing demand for housing and commercial developments in the twenty-first century, as well as the environmental pressure has increased the focus on sustainable urban drainage and waste management systems.
- *Improved operational management*: To achieve energy efficiency in a building, energy system operation and management is vital. Control devices are usually incorporated into the energy system. However, poor control design, poor management, and a lack of knowledge of occupants' behavior and expectation results in significant energy waste. Research into better management practices, alternative technologies, and the provision of feedback loops are needed.
- *Understanding occupants*: Research into end-user behavior on energy consumption in buildings is required, particularly in residential buildings (Ouyang and Hokao 2009). Key questions are the provision of improved, clear information to assist occupants with managing energy consumption, managing expectations, and gathering data on actual performance.
- *Embodied energy*: There is widespread use of highly energy-intensive building materials, and little consideration for life-cycle issues. New standards for building materials are necessary along with new planning and design processes to include embodied energy and increasing the longevity of buildings. The authority for building materials and energy efficiency standards are currently in separate agencies, rendering the development and subsequent enforcement of standards for building materials problematic.
- *Renewable energy and exergy*: Although highly energy efficient or nearly net 'zero carbon' buildings will reduce energy demand, some demand will remain in the building stock for space heating, hot water, and appliances, etc. Decarbonization of the built environment will require a combination of demand-side and supply-side measures. The supply and cascading of energy will become an issue for strategic planning at the city and town levels. There is a need to establish relative technical and economic merits of the different options for renewable energy sources for heat supply to urban areas to replace fossil fuel energy. The issues of balancing heat supply and demand need to be clarified and

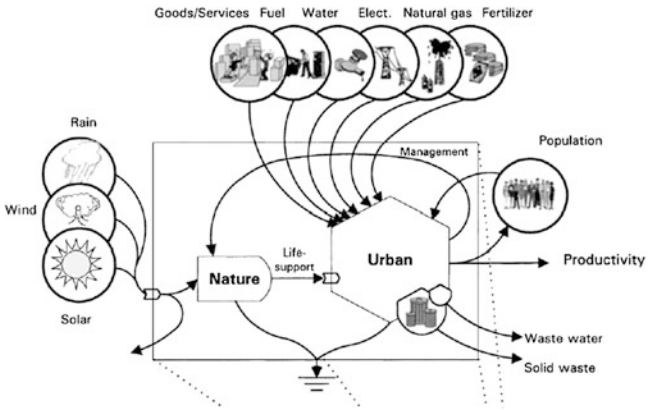


**Fig. 1.6** A conceptual diagram representing energy flows in Taipei (*source* Huang et al. 2001)

understood. Renewable energy such as ground source heat pumps, wind, and solar energy can play a major role for rural communities and low-density developments. The control and management of integrating the complex interactions of humans, climatic phenomena, building operation, and energy systems is a key measure.

Sustainable urban environments are systems. They comprise of many components with inputs and outputs. When attempting to model the complex energy flows and interactions between the components, *systems modeling* can be drawn upon to provide a framework in which to facilitate such an exercise. In 1971, ecologist Howard Odum and colleagues developed an energy systems language, initially used for ecological modeling. This language involved the use of symbols to represent energy flows and processes. Using Odum's system, Huang et al. (2001) suggest that the principles of ecosystems can be applied, in general, to other systems—cities. Odum's system generates a layered hierarchy of *energy* consumption ('energy' being the total quantity of energy consumed to acquire something, measured in Solar Joules). Figure 1.6 shows Huang's representation of a city (Taiwan) illustrating the energy inputs and outputs to and from the city. The concept is a useful tool when considering urban sustainability as it links humans with their energy demands and activities.

Another concept that falls into this line of enquiry is *maximumempower*. The 'maximum empower principle' states that organic systems are self-organizing, whereby they arrange themselves to make the best use of the energy they consume through use of control and feedback mechanisms. Again, parallels can be drawn between cities and eco-systems here. Although energy systems modeling and energy accounting are not featured in detail within this book, it is worth noting the principles as energy system modelers use *energy* analysis for modeling energy flows in sustainable systems. Those of which include buildings.

## 1.5 Policy

Since the oil crisis in the 1970s, the energy agenda has slowly worked its way to the top of conversational topics; being one of the most widely discussed today. Whether talked about in political corridors, boardrooms or bedrooms, energy impacts on each and every one of us. And in some instances; profoundly. Tagged to the notion of energy security and economic stability, is *environment*. Debates began to broaden during the 1980s when environmental concerns were ushered into the limelight, bought about by oil spills, drought, global temperature rises (Fig. 1.5), ozone depletion, and the like. A year after the Brundtland report's release, The *United Nations Environment Programme* and *The World Meteorological Organization* formed IPCC. It is responsible for assessing climate change risk. The panel released a series of reports (1990, 1995, and 2001), with the most recent fourth assessment report (AR4) in 2007 (IPCC 2007a, b). Heralded as one of the most comprehensive climate change studies ever undertaken, AR4 states within its summary that: *'the increase in observed average global temperatures is very likely due to anthropogenic greenhouse gas concentrations'*, estimated to have increased by 70 % from 1970 to 2004. The report findings are generally considered 'compeling evidence' within the scientific community, substantiating climate change. The report suggested that through improved energy efficiency, approximately 30 % of the projected greenhouse gas (GHG) emissions in the building sector can be avoided with a net economic gain.

A comprehensive suite of international policy measures have subsequently been introduced, including: the *United Nations Rio Earth Summit* where *Agenda 21* (UN 1992) was created; the *Kyoto Protocol* (UNFCCC 1997) which set legally binding emission reduction targets; the *Johannesburg Summit* (UNFCCC 2002) proposing a road map; the *Copenhagen Accord* (UNFCCC 2009) that stipulated a 2 °C temperature increase limit; and future UNFCCC efforts that will undoubtedly provide additional policy (e.g., Doha in 2012).

### *1.5.1 UK Policy*

The UK is politically ambitious in this area. Having introduced the *2008 Climate Change Act* (DECC 2008a, b), supplemented by *2008 The Energy Act* (DECC 2008a), and the *2009 Low Carbon Transition Plan* (DECC 2009), the UK arguably has the toughest climate change policy in the world. And with a target of reducing emissions by 2050 by 80 % from a 1990 baseline, a multifaceted approach is essential. Facilitated by these acts, numerous programs and schemes have been rolled out nationally; each one, attempting to reduce carbon emissions using differing mechanisms. For example, the *Low Carbon Buildings Programme* (DECC 2006) was a £137 million suite of grant program aimed at bolstering the acquisition and installation of Microgeneration technologies over a six year period.

Other financial mechanisms include *The Warm Front Scheme*, part of the *UK Fuel Poverty Strategy* (BERR 2001), introducing subsidies and grants worth up to £3,500 per site (or £6,000 where renewable technologies are recommended) in reducing heat loss; and *The Boiler Scrappage Scheme*, co-ordinated by the energy saving trust (EST), issued homeowners with a voucher worth up to £400 which could be used to partially offset the capital cost of upgrading their existing boiler.

Aside from this, UK government also uses the *Planning* system and *Building Regulations* as powerful mechanisms for leverage. The *Merton Rule* (stipulating that new developments need to generate at least 10 % of their energy needs from on-site renewable energy equipment) coupled with the progressive tightening of building standards (Lim and Yao 2009) that address issues such as thermal insulation in Part L, are all weapons in the armoury to bring about change. In addition, building assessment methods such as the government's standard assessment procedure (SAP), the code for sustainable homes (CSH) and the BRE environmental assessment method (BREEAM), all provide extra tools in the battle against climate change.

## 1.6 Design and Management

Buildings facilitate a hive of activities from domestic purposes to industry, to administration to leisure, and beyond. Buildings are central to life. Not least providing shelter, but when designed and managed successfully, they can promote social interaction, foster well-being, bolster productivity, and support cultural advancement.

The commonly quoted statistic is that buildings consume in the range of 40–50 % of total energy consumption in developed countries, globally, and on a country basis (DECC 2010; IBE 2011; IEA 2012). Possible discrepancies occur due to the inclusivity of construction materials. Incidentally, this figure is true for the UK and mirrors findings by the *European Commission for Energy* (2010) who found that buildings are responsible for 40 % of energy consumption and 36 % of total European $CO_2$ emissions. All said these gloomy statistics present an ideal opportunity—the opportunity to reduce a significant quantity of carbon emissions from within the sector. Naturally, we ask ourselves—*how can this be achieved?*

When searching for answers, it is worth noting a building's *energy end-uses* (i.e. HVAC equipment, space heating or cooling, domestic hot water, lighting, appliances, and other miscellaneous building services). In doing so, it provides some valuable clues. Focusing on these end-uses and thinking 'vertically', it is evident that careful consideration of: (1) urban planning; (2) architectural design; (3) energy supply and demand; (4) climate; and (5) the way we operate our buildings hold the key to cutting carbon emissions.

### 1.6.1 Urban Planning

Urban planning addresses energy use at a high level. And getting it right can help harmonize our existence with the environment. From the organic development of towns during the Classical period, to the first planned cities of the Egyptian and Mesopotamian eras 3000 BC, to the eco-cities in the Middle East, the importance of good urban planning cannot be overstated. Early decisions have long lasting consequences.

Land use, road, rail and pedestrian networks, transport links, street plans, building density, and layout, all these issues can have profound impacts on the longevity of a city's energy consumption. Ill-considered planning can result in poor urban ventilation, unsatisfactory levels of urban comfort, dysfunctional spaces, the exacerbation of the urban heat island effect (UHI), and lack of green spaces that promote well-being. Figure 1.7 shows an iconic graph (Newman and Kenworthy 1999) illustrating the hyperbolic relationship between urban density and energy consumption. It is worth noting here that European cities have a relatively low energy consumption as well as urban density.

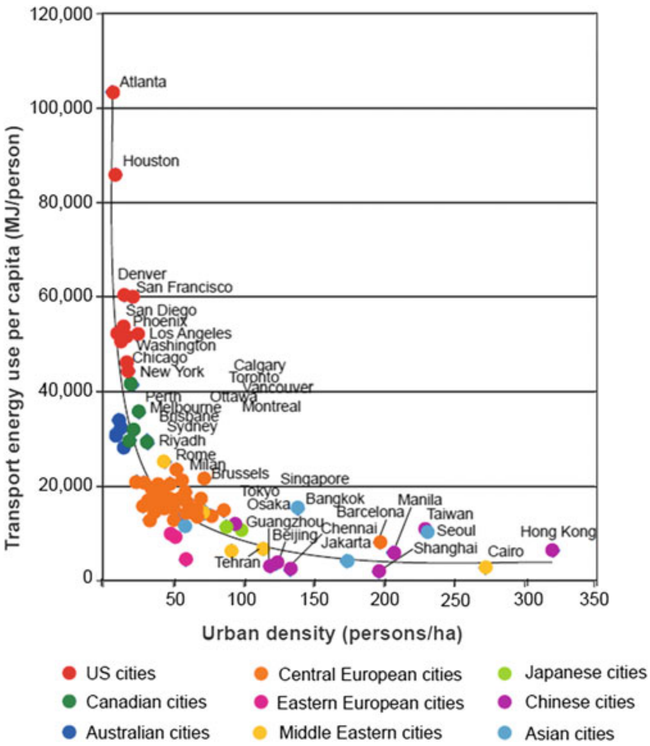


**Fig. 1.7** Relationship between urban density and energy consumption (Newman and Kenworthy 1999, updated in 2012 provided by Prof. Peter Newman with permission of use)

Sustainable urban planning is a relatively new concept. At one end of the spectrum are established cities that strive to be ecologically friendly, retrospectively; while on the other, swirl the engineering dreams that are maturing into a reality, in the desert. Masdar Eco-city, Abu Dhabi is a $22 billion dollar, 10 year project. Due for completion in 2014, it will cover 6 $km^2$, will be the home to 50,000 people, 1,500 businesses and is powered by 200 MW of renewable energy technology (a solar plant, photovoltaic modules, and wind turbines). Cars are banned, so inhabitants use a *mass public* and *personal rapid* transit system, with silent electric vehicles criss-crossing a blocked layout. China, one of the countries with largest construction market in the world, moves to sustainable low carbon eco-cities development. For example, Sino-Singapore Eco-city covers 30 $km^2$ and accommodates 350,000 residents aimed to become a showcase of sustainable development of cities/towns and serve as a model for sustainable development for other cities in China (http://www.tianjinecocity.gov.sg/). Its vision is to be a thriving city which is socially harmonious, environmentally friendly, and resource-efficient.

### *1.6.2 Architectural Design*

Arguably the most noticeable component of sustainable urban environments is its buildings. Under the umbrella term *sustainable architecture*, a whole raft of factors comes into play. Figure 1.8 shows some of the key themes which shape the practice of modern day architecture from a sustainability perspective.

It is evident that the concept of sustainable architecture goes beyond the physicality of the building itself, but instead, views it as a holistic process. It

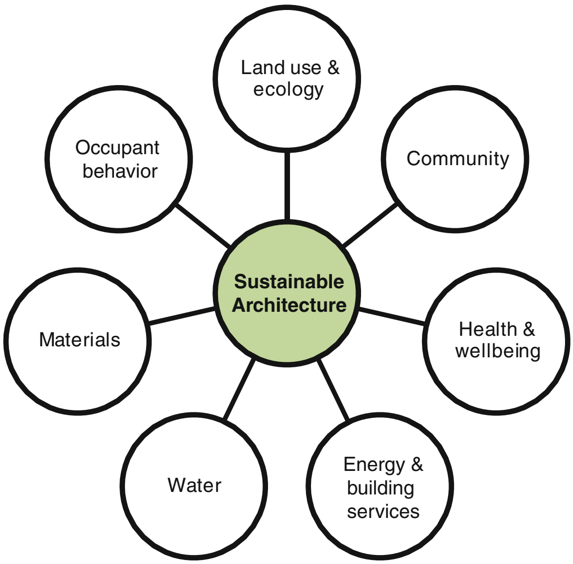


**Fig. 1.8** Sustainable architecture and associated factors

emphasizes context. And it emphasizes its connection with environment and people through ideas about community, occupant health, and wellbeing. Building material resource and their availability are also considered. Sustainable architecture asks questions about: how to use materials more efficiently; how are they sourced; and are they renewable? And, as one expects, minimizing operational energy consumption is always at the forefront of design. An attention is paid to the impact of form (shape, texture, aspect ratio, glazing, etc.), building services (e.g., heating/cooling systems), local climate, and thermal performance at the early stage of urban planning.

The concept of *carbon lock-in* is also worth mentioning here. The term commonly refers to instances where systems are installed (e.g., heating), with a *fixed* efficiency, and remain irreplaceable for many years, usually for its engineering lifetime due to high replacement cost or service disruption. Inability to replace, users are ‘locked’ into a time period, during which time that system produces significant carbon emissions compared to more efficient systems. Carbon lock-in occurs within the design of building envelopes (building’s ‘skin’ construction) as well as building services. Upgrading or improving the performance of the existing building stock is known as *retrofitting*: an up and coming area within industry.

With a demolition rate of 1 % in the UK, unsurprisingly nearly all the buildings by 2050 (approximately 70 %) are already standing today or in the planning phase (BRE 2012a, b). What is clear is the need to engage with building maintenance and refurbishment of the existing building stock, combined with efficient facilities management processes to sustain energy savings in the long term. Roberts (2008) and Boardman (2007) discuss the enormity of this challenge and the policy mechanisms available to government to enable industry and homeowners to tackle such issues.

Another concept that heavily features within sustainable architecture is *passive design.* Passive design utilizes the principles of building physics to enable building services to operate without using energy (or very little). Techniques range from correct building orientation to maximize sunlight in reducing heating and lighting energy demand, to more elaborate ideas such as multilevel displacement ventilation that uses natural air buoyancy effects to replace the need for mechanical ventilation. Within industry, a Passive Standard exists—*Passivhaus*. Quoted as the fastest growing energy performance standard, some 30,000 Passive buildings have now been built internationally (BRE 2012a, b).

### *1.6.3 Waste and Water*

Water is essential to life. Buildings use water: *potable water* for occupants to drink, and *non-potable water* for other uses such as flushing toilets, industrial processing, and other utility. It comes as no surprise that urban environments use water, and a lot of it. With climate change forecasts predicting increased frequency of floods and drought (IPCC 2007a, b), the manner in which we manage water will be of utmost importance. Water security has received increased attention over the past decade in both policy and in academic circles (Cook and Bakker 2012). Reducing water consumption therefore, is vital for the security of food production, servicing buildings, essential human activities, and many other uses.

Water sustainability from a building services approach, includes an abundance of technologies, from spray taps with sensors, to gray and rain water recycling systems, to full on-site waste water treatment plants. Green roofs will also help with sustainable urban drainage and bio-diversity.

With the reduction of energy, comes the reduction of waste. The two being synonymous. It is frequently voiced that 'we live in a throwaway society'; that it is cheaper in many instances to replace products compared with repairing them. This type of society will continue to flourish, until waste and resources become prohibitive factors. The parameters of *time* and *consumption discount rate* have been found to be significant predictors of municipal solid waste (MSW) per capita (McCullough 2012). The indirect cost of time to maintain a product, and when it breaks, shop for and purchase a replacement, often outweighs the desire to reuse it. Consequently, those with higher incomes fall prey to this notion. Second, if the benefits of repair are equal or less to those of replacement, then replacing is generally favored. For example, if repairing a broken kettle costs as much as replacing it with a newer and better alternative (with more features and a warrantee), then repairing it seems unattractive. Waste, be it electrical appliances, paper, glass, plastic, timber, industrial, food, or garden waste, and even metal that is increasing in 'raw material' value, appears to be continually generated on mass. The resulting diminution of landfill sites has caused much concern within environmental politics and the waste management industry. Furthermore, our planet's needs sustainable environments to implement robust waste management strategies and recycling processes to help protect its resources.

### *1.6.4 Energy Supply and Demand*

With a headstrong desire to meet the energy needs of new populous cities and megacities, the question of energy supply and demand comes into sharp focus. The energy supply mix remains heavily reliant on fossil fuels (coal, oil, and gas) in which to generate electricity and heat. Although the UK energy output of renewables has increased since 1996 (Fig. 1.9), primarily driven by policy, its uptake is not anywhere near the rate required to deliver the 'paradigm shift' that's needed to seriously curb the harmful effects of climate change

Decarbonizing the electricity grid continues to present new challenges (Shackley and Green 2007), however the talk of 'smart grids' and microgrids, combined with intelligent energy management systems, smart meters and renewable energy technology widens the scope for a more sustainable energy distribution network. The diffusion of building integrated renewables (e.g., solar photovoltaics, micro-wind, solar thermal, and biomass boilers) appear to be

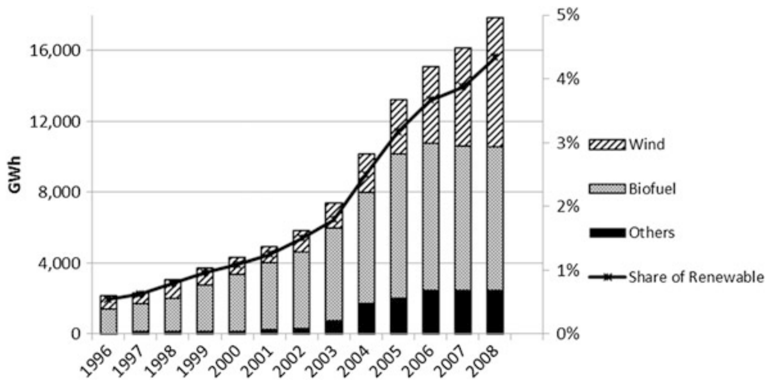


**Fig. 1.9** UK Renewable energy generation (Renewable obligation basis) (*Source* ONS 2009)

bolstered by policy instruments such as planning and the *Feed-in Tariff*, guaranteeing a price for each kWh of electricity generated which is fed back into the electricity grid. Fortunately, early teething problems in the renewables supply chain seem to be dissolving, increasing the public's perception, and acceptability of various technologies across the urban landscape.

Operating on the opposing side of the energy equation is demand-side management (DSM). At a high level, demand-side initiatives tackle energy reduction at a national, regional, and city-scale. Spacial planning, urban transport, infrastructure, and social housing are typical issues on this agenda. In the Chinese context, where urban sustainability issues require urgent attention, Li and Yao (2012) look into the research challenges and opportunities involved in building energy efficiency. Discussing on policy, technology and implementation, they comment on the state of current affairs, developmental progress, and future direction. In their conclusions, they state that: (1) policies, standards, codes, and assessment tools, together with strict compliance procedures are necessary; (2) R&D, technology innovation and implementation programs should be carried out continually to help identify new research challenges, provide lessons, and raise public awareness of sustainable development; (3) there is an urgency to develop *tools* to help with project life cycles, planning, facilities management, and post occupancy evaluation in an integrated fashion; and (4) understanding building users' energy demands, expectations, behaviors, and lifestyles is vital when striving to create a resource conservation society. An emphasis on *integrated thinking* emerges from their work. When drilling down to a building level, operational management, and challenges associated with changing occupancy behavior are more pertinent (Yu et al. 2011). This is covered later in the sub-section entitled 'management'.

### 1.6.5 Management

Occupant behavior and the manner in which we operate our buildings is arguably more important than the building itself (Janda 2011). There is little strength in high performance materials and outstanding build quality if the building's users do not operate the building as it was intended. This notion asserts the importance of the role in which occupants play in determining the overall energy consumption of buildings. An influential paper by Wood and Newborough (2003) cites studies from the US (1978), Holland (1981), and the UK (1996) which found that occupant behavior alone was responsible for 26–36 % of total domestic energy use. Other studies report that occupancy issues could vary the consumption of identically built houses by a factor of two (Seligman et al. 1978; Baker and Steemers 2000) or even three (Shipworth 2010).

Facilities managers are expected to increase their engagement with operational issues, while householders are faced with reducing demand through interventions associated with the building's energy end-uses. DSM programs attempt to typically influence when we use energy, characterized by financial incentives inherent in pricing tariffs. Energy behavioral awareness is bought to our attention through public information services, utility companies, schools, and other organizations. Commonplace, are messages telling us to 'switch off lights', 'turn our heating down', and to 'conserve water when washing the dishes'. Influencing behavior change is hugely challenging as deeply ingrained behaviors are difficult to re-shape (Stephenson et al. 2010). Tackling the management of buildings requires a holistic approach and one that is implemented with care and insight, avoiding the potential pitfalls.

### 1.6.6 Technology

If a fourth pillar was proposed in shaping the definition of sustainability, it would reflect *technology*. Indeed, the institute of development studies (IDS) has a center with the acronym social, technological, and environmental pathways to sustainability (STEPS). It is without any doubt that sustainable development depends pivotally on technology. In an early study that looked at intervention policies to achieve a 'sustainable city', Camagni et al. (1998) derive solutions based on *technology*, territory, and lifestyle strategies. Technology blossoms and provides us with new innovative products at an alarming pace. Information technology (IT), renewable energy technology, building services technology, and sensor technology, are all incremental in providing us with solutions for sustainable urban environments—now and for the future.

When it comes to buildings, technology is at the forefront in achieving sustainability. Building structures, the building envelope, building services, and the equipment found in buildings all reply on technology in one form or another.

Considering the existing building stock and the retrofit boom that is about to occur, the industry will rely heavily on technological solutions in providing answers to some very complex problems. What systems and materials will best integrate with existing structures and services? Turning toward new buildings, technology has the potential to overcome typical pitfalls by providing cutting-edge solutions. The development of phase change materials, wireless sensor networks, holistic energy management systems, and web-enabled services will all contribute to the intelligence of buildings in the near future, and for some already built. Exciting eco-city projects such as those in Masdar, Abu Dhabi, and Eco-cities in China will undoubtedly set the trend for technology in future sustainable built environments. One example is the exclusive use of electric vehicles to get around the city at Masdar.

Information technology and computing has enabled the modeling, simulation and analysis of systems, and processes within many areas of the built environment. Using computational techniques to implement mathematical equations, computational fluid dynamics (CFD), and generic algorithms can enable analysts to model a multitude of phenomena that occur within urban environments. By no means an exhaustive list, this includes the analysis of: energy (energy and exergy) flows, resource flows, transport movement, microclimates, indoor environments, acoustics, heating, cooling, ventilation, air conditioning, natural and artificial lighting, appliance use (Lim and Yao 2012), and structural components. Aside from building physics processes, computing can also aid in modeling occupant behavior (actions), environmental, and social and economic systems that are also integral to sustainable urban systems.

## 1.7 Conclusion

The principles of sustainability draw together many facets, not least of which include those governing environmental, economic, and social interactions. Applying the concepts of sustainability to the urban environment (buildings, infrastructure, transport, etc.) raises some key issues for tackling climate change, resource depletion, and energy supply. Buildings and the way we operate them play a vital role in tackling global greenhouse gas emissions. In addition, international policy is well established in supporting carbon reduction and the UK in particular has set some challenging targets aimed at reducing energy from the buildings sector. With the aid of planning systems, building regulation, and green building assessment methods, new urban developments are tightly controlled and foster a culture of energy efficiency together with social enhancement, an area of construction that previously received less attention. Other factors such as water, waste, energy supply, and demand are also keenly observed in policy measures and mechanisms. Engaging with energy efficiency in the context of an old building stock is presenting unique challenges that require careful approaches in providing answers. It is recognized that technology will play a huge part in enabling industry to deliver robust solutions that are fit for purpose. Further to this, information technology and advances in computing science will increasingly feature in building energy management and influence how we interact with indoor environments. It appears that a common message is repeated within the literature which underlines the need for holistic thinking and an integrated approach. Finally, as we head into an uncertain future with demographic and climatic change at our doorstep, combined with resource depletion and energy security issues, striving to achieve sustainable urban environments becomes a prerequisite if mankind is to thrive on Earth.

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# Chapter 2
# Buildings and Climate Change

**Neil Hirst**

**Abstract** This chapter provides the global context for the need to reduce energy and GHG emissions associated with buildings. It starts by highlighting the target of containing the average increase in global temperatures to 2 °. Furthermore, it demonstrates the important role that buildings (their services and appliances) and building energy policy play in this area. Substantial investment is required to implement such policies however much of this will earn a good return. The chapter goes on to examine differences between the developed world (where improving the efficiency of existing buildings is the main challenge) and the developing world (where new buildings are more important). The cost of intervention is later explored. Low cost options such as basic home insulation are the first priority. However, meeting the 2° target will undoubtedly eventually require the adoption of higher cost options, such as installing heat pumps. Finally, this chapter underlines the need for further research and development, including pilot schemes to pioneer more advanced technologies and systems that are needed to realize the deepest carbon emissions cuts. *Learning outcome*: On successful completion of this chapter, readers will be able to: (1)demonstrate a basic understanding of the role that buildings play in tackling carbon reduction targets; (2) have knowledge of the principle mechanisms in reducing energy in buildings; (3) appreciate response differences in reducing carbon emissions in buildings between the developed and developing world; (4) reflect on the complexities, challenges, and need for further work in this area in order to better understand the future role of buildings.

**Keywords** Building efficiency · Carbon reduction cost · Climate change · Low carbon policy · Low carbon development

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## 2.1 Introduction

Buildings provide the physical framework of our lives and of almost all our energy use. Even our needs for transport are framed by the layout of the villages, towns, and cities in which we live. Unfortunately, the living standards that we enjoy in the developed world are currently underpinned by a stock of buildings that is oriented toward high energy consumption; developed countries however only represent about one sixth of the world's population. The rapid economic progress and enhancement of living standards that is taking place in countries such as India and China is also, in part, a transformation of the built environment. If we fail to curb the energy intensity of our own buildings in the developed world, and if the developing world follows in our footsteps, the consequences for energy demand and for $CO_2$ emissions will be disastrous. This means that understanding the sustainability of buildings, the subject of this book, is critical for the future of our planet.

## 2.2 The Climate Change Crisis

Global temperatures are already rising due, in large measure, to energy related $CO_2$ emissions. The *Copenhagen Accord*, which was ratified by world leaders at the *Copenhagen Climate Summit* in 2009, established a target of containing the average increase in global temperatures to 2 °C. That target is, almost certainly, already beyond reach. It would require global emissions to peak before 2020 whereas, even taking account of the Copenhagen national targets, they are not now likely to peak before 2035. According to the *International Energy Agency* (IEA), either the 2020 targets would have to be revisited or the speed of the transformation that would be required after 2020 would need to be extraordinarily rapid (IEA 2010c).

The world may therefore be on course for an increase in average temperatures in excess of 3.5 °C (IEA 2010c). This assumes that governments will actually meet their own national targets, also announced at the 2009 climate summit, for curbing the growth of $CO_2$ emissions. If governments do not adopt the necessary policies, we may be heading for a temperature increase in excess of 6°. This scenario conjures up an alarming picture. Even a rise of 3.5 ° could well have severe effects on water supply and crop productivity and lead to coastal flooding, the extinction of species, and the spread of disease. There is considerable uncertainty about the full extent of these effects, but we do know that they are likely to be concentrated in some of the poorest parts of the world, for instance in Asia and Africa. The consequences of a 6° rise are unthinkable (Green Alliance 2011).

This grim environmental outlook is the result of the global spread of the industrial revolution which, in other respects, has been, and should continue to be, a great blessing for mankind. For the first time in history there is the prospect of decent living standards for the majority and not just for the minority. China alone, by sustaining a breathtaking level of economic growth in recent decades has achieved: *'the most rapid decline in absolute poverty ever witnessed'* (UNDP 2010). Nevertheless, China still has a huge population living in poverty.

On average, people in the Organisation for Economic Co-operation and Development (OECD) countries consume more than twice as much energy per capita as the global average and, for instance, more than five times as much as the average person in Asia. It is inevitable that, without a radical change in technology, the advance of living standards in the developing world toward those in the OECD will imply a huge increase in energy supply and fossil fuel consumption, a fact that is all too evident in current trends.

Most of the projected growth in energy demand in the coming decades is attributable to developing countries, including China, India, Brazil, and South Africa (IEA 2010c). These countries are aware of the threat that climate change poses and of the need for mitigation. Furthermore, they are all signatories of the Copenhagen Accord (2009). This Accord contains the 2 ° target but it also recognizes, specifically, that: *'social and economic development and poverty eradication are the first and overriding priorities of developing countries'*. The Accord also contains a commitment by the developed countries to mobilize $100 billion per annum by 2020 to help developing countries to address their mitigation needs.

In spite of the dominant role of developing countries in future emissions growth, it is the relatively rich OECD countries that will need to act first. This is because it was the OECD countries which initially created the problem (being responsible for the majority of greenhouse gas in the atmosphere today), because the level of emissions per head in the OECD is so much higher than in the developing world, and because, at present, it is the OECD countries that have the resources necessary to tackle the problem.

Developing countries are willing to follow the 'rich' countries in pursuing carbon reduction policies, but only if they are certain that this will not stand in the way of poverty alleviation and raising living standards. From this point of view, the adoption of low cost improvements in the efficiency of buildings represents a particularly attractive option because it can free up energy supplies, which are often tightly stretched, to meet other development needs.

With current policies, global energy related $CO_2$ emissions (which make up about 70 % of all greenhouse gas emissions) are set to double from about 28 billion tons per annum today to 57 billion tons per annum in 2050 (IEA 2010a). By contrast, a strategy for containing global warming to around 2–3 °C requires a halving of today's emissions to 14 billion tons in 2050. The reduction needed in projected 2050 emissions is greater than total emissions today. Of course, developed countries will have to make a much greater proportional contribution. For instance, the statutory target set by the UK is for an 80 % reduction in emissions by 2050.

While renewables, nuclear power, and carbon capture and storage (CCS) all have to make major contributions, the greatest potential $CO_2$ reductions will need to come from greater efficiency in the way we use fuel and electricity. This is estimated by the IEA to be nearly 40 % of the total (IEA 2010a). Buildings, together with the equipment and appliances they contain, have a crucial role in this.

## 2.3 The Building Sector

Achieving the necessary level of carbon reduction within the buildings sector is a monumental global challenge. The first stage involves effective regulation and enforcement to ensure that all currently available low cost carbon saving options are achieved. Particularly for developing countries, this means stronger regulation and the development of effective national and regional enforcement agencies. Subsequent stages require focusing onto the application of more advanced, and sometimes costly, measures and technologies required to reduce emissions to significantly lower levels.

The IEA's (Blue Map) low carbon case suggests that \$7.9 trillion of additional investment is needed in buildings within the residential sector between now and 2050 and \$4.4 trillion within the service sector. These are huge sums, but they equate to less than 1 % of global GDP. Savings of 5.8 billion tons of $CO_2$ emissions are intended to be created by these investment measures. Together with a saving of 6.8 billion tons of $CO_2$ from the decarbonization of electricity used in the sector, this achieves an 83 % reduction in buildings related emissions in 2050 (IEA 2010a).

The majority of this immense expenditure on buildings efficiency will eventually earn a good return in fuel savings. The total estimated value of the fuel savings to 2050 is \$51 trillion. In time, the value of efficiency gains will exceed initial capital investments, even at a commercial discount rate of 10 % (IEA 2010a).

These figures not only illustrate the scale of the task, but also the vast range of opportunities for business and employment that will arise from its achievement. They also highlight the fact that the buildings sector offers some of the most cost-effective measures available for addressing climate change.

In spite of the great opportunities it presents, the buildings sector often appears as a poor relation in the climate change debate and governments have found it extraordinarily difficult, in practice, to reap the carbon savings on offer: 'between the idea and the reality falls the shadow'. The climate mitigation debate tends to be dominated by the supply side, in which nuclear power and renewables contend for dominance with carbon capture and storage. The importance of buildings is often not adequately reflected in *pie* and *wedge* charts in which savings in the buildings sector appear as unspecified efficiency gains, or in the case of heating electrification, are attributed to low carbon generation.

It is true that if we had at our disposal, unlimited supplies of low cost carbon free electricity, the decarbonization of buildings would not be a problem. In reality, however, none of the options for low carbon electricity is likely to be cheap or easy to deliver on the scale required. This means that for the foreseeable future we will continue to rely on policies for reducing energy in buildings, as well as policies for low carbon energy supply.

## 2.4 The Developing World

The need to supply decent homes for large numbers of poor people is one of the primary drivers of economic development in major developing countries such as China or India. Indeed, largely for this reason, almost half of the world's construction is currently taking place in China. This is where the megacities of the future are now being created. China is now producing more than half of the world's cement, and as a result, China's cement industry alone is emitting almost twice as much $CO_2$ as the entire UK economy (IEA 2010b). Construction is nearing its peak in Eastern China, and will probably peak in Central and Western China within the next 10–20 years. Furthermore, Chinese buildings standards are generally lower than in the West. Reputedly, there is inadequate buildings inspection and anecdotal evidence suggests that a proportion of new buildings fall far short of planning specification, insulation thickness being a typical example.

These buildings exemplify the concept of 'lock in', where high levels of $CO_2$ emissions are inherently produced for many years until major refurbishment. Alternatively, those of the poorest quality may need to be replaced, bearing in mind that average building life in China is only about 30 years. Either outcome will place a heavy burden on the environment.

*Berkeley Laboratory* in the USA has famously estimated that by 2020, tough new standards for appliances in China will be delivering efficiency improvements equivalent to more than five times the output of the *Three Gorges Dam*, the world's largest hydro-electric plant (Fridley and Zheng 2010). There is a strong case that Governments concerned with reducing the global level of carbon emissions should concentrate on supporting the efforts of cities and provinces in China's Central and Western regions to enhance building quality, especially by training and deploying a strong force of buildings inspectors.

## 2.5 The Developed World

While new buildings present the greatest opportunities for carbon savings in the developing world, only a small percentage of the housing stock is replaced each year in the developed world, 1 % in the UK (DCLG 2011), and therefore it is the upgrading, or retrofitting, of existing buildings that is most important.

Basic measures to provide adequate insulation, to install quality doors and windows, exclude drafts, and install best practice systems as standard (such as condensing boilers), will radically improve the efficiency of most homes in the UK. This also holds true for achieving energy efficiency in other temperate parts of the world. These are mostly low cost measures that incorporate well-established technologies with acceptable or good payback periods.

The irony associated with high performance buildings (or the results of building retrofitting) is the *rebound effect* or *take-back factor*. This is characterized by improved levels of comfort, often in the form of higher internal temperatures, taken at the expense of energy savings. Historically in the UK, when homeowners switched from open coal fires to gas central heating, many took extra comfort in the form of day and night heating of the whole house (Hawkes et al. 2011).

## 2.6 Low Cost Options

The IEA has listed the basic measures which governments need to take in order to promote greater energy efficiency in buildings. They include: the strengthening and enforcement of codes for new buildings; better information on the efficiency of existing buildings; mandatory building standards whenever a building is sold, rented, or constructed; and high efficiency windows and other glazed areas. The IEA's latest estimate is that overall, their member countries achieved 43 % full or substantial implementation, but that 57 % of those measures are at best, work in progress (IEA 2011).

However, in most countries these measures, which are largely voluntary, have so far only scratched the surface of the problem. Only a small proportion of existing houses have been significantly affected and there is a lack of rigorous measurement of the fuel savings actually achieved. Solid wall housing, where additional insulation has to be applied to the inside or the outside of external walls, represents a particular problem. For instance, the UK's 'Fourth Carbon Budget' for 2023–2027, stipulates that approximately 8 million solid wall dwellings must be insulated through the 2020s and beyond.

One promising approach is to progressively tighten regulations for existing buildings through systematic retrofitting, implemented on a 'street by street' basis. However, in a democracy, and perhaps other forms of government too, such measures are politically unfeasible in the absence of a real public sense of crisis over climate change.

Another irony is that the economic return on many energy efficiency measures in buildings is high by commercial standards and is higher than the rate of return required by power companies on their investment in energy supply. Efficiency measures are often not implemented due to high capital investment costs incurred by the homeowner; likewise, in the case of rented or leased property, both the tenant and landlord may fail to instigate any refurbishment due to the lengthy payback periods involved. A number of efforts have been made to overcome this barrier, for instance through energy service ventures. Most recently, the UK Government's *Green Deal* represents an ingenious attempt to improve the security available to utilities and other providers entering into service contracts with consumers.

## 2.7 Intermediate and High Cost Options

The previously mentioned, low cost options are only part of the story. If we are to limit expected global warming to 2 °C, as required by the Copenhagen Accord, we will need to reduce carbon emissions to exceptionally low levels. The basic low cost measures described above will not be sufficient to achieve this degree of carbon reduction and it is clear that more radical options will need to be adopted.

What options are available? Sustainable building design can maximize the use of *passive* strategies for heating, cooling, ventilation, and lighting, through careful management of solar heat gains for example. Sustainable design can also minimize heat loss and store heat in building structures using the property of thermal mass. There is a current trend for high performance homes to use *air source heat pumps* (ASHP) with a *heat recovery* system. Heat pumps, which concentrate low grade heat in the surrounding air or underground, can provide heating equivalent of up to five times the energy they require. District heating can distribute 'free' heat from power stations or industrial plant and can also exploit organic waste in biomass systems. If the energy demand of buildings could be reduced to exceptionally low levels, then energy generated by local or micro-renewables, including PV surfaces integral to the buildings themselves, could potentially meet this demand.

Technology optimization can be complex and is often case specific, dependent on factors such as climate, planning regulation, physical constraints, and financial implications. For instance, district heating might prove optimal where 'free' heat, or possibly biowaste, is available close to high demand locations and ground source heat pumps (GSHP) require access to suitable land for either boreholes or loop systems. Local renewables might include small scale hydro, wind, and gas from anaerobic bio digesters.

Complex interactions will inevitably arise in a low carbon built environment where a significant proportion of energy supply originates from renewables which provide intermittent generation, such as wind turbines and solar photovoltaic panels. In addition, the transport sector will employ an increasing quantity of electric vehicles which will place additional demands on electricity distribution networks. Smart grids of the future will continually balance demand and supply for electricity and the heat storage capability of buildings is expected to make an important contribution to the stability of the system, both locally and nationally.

Further research is needed to better understand the transition to such a sophisticated and dynamic energy future. In addition, research is also required to improve the performance, reduce the cost, and optimize the deployment of advanced low carbon technologies such as PV and heat pumps.

Is this kind of transformation feasible over the coming decades? It would be comparable to the almost complete replacement of household heating in the UK, from coal to natural gas, which commenced in the 1970s (Hawkes et al. 2011). The incentives for consumers were powerful in this particular case; natural gas proved more convenient and transformed comfort levels. For a similar transformation, the incentives would need to be exceptionally attractive or the regulation very tough, in order to achieve a comparable shift. Conclusions emerging from a recent Grantham/IEA workshop (Jennings et al. 2011) suggested that in an ultra-low carbon world, energy costs will be much higher and the social implications of this need to be addressed.

## 2.8 Conclusion

Reducing the carbon intensity of buildings and the services they provide, is a vital part of the struggle to mitigate climate change. It is essential to secure the benefits realized by conventional low carbon technology in the early stages. In achieving such aims, developed countries should take a lead role and support the developing nations to put in place proved strategies governed by sound regulatory bodies. Additionally, developed countries should also commit the investment in research and development (R and D), and pilot schemes, to pioneer the more advanced technologies and systems that are required to bring about very deep level $CO_2$ reductions for the future built environment. The policy options are diverse and implementing tough legislation that is practical and cost- effective will be challenging for governments in developing, and developed countries alike. This book addresses the key themes of sustainable design within the built environment and is an essential aid to those who are studying and researching in this area; and working on the monumental challenge ahead of us.

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# Chapter 3
# Low Carbon Sustainable Urban-Scale Masterplanning

**Phil Jones**

**Abstract** This chapter discusses the need for energy and environmental modeling at an urban scale. It stresses the importance of carrying out such modeling at an early masterplanning stage of a new development. It also considers modeling the existing built environment at urban scale and how this can inform retrofit programs. A variety of modeling methods are introduced, from simple annual energy calculations, to how more complex energy models developed for individual building simulation can be applied at an urban scale. The use of physical-scale modeling for environmental predictions is also discussed. The chapter uses a range of urban case studies to illustrate the modeling applications. Finally, a general framework for sustainable urban-scale masterplanning is introduced. The work is based on the development of urban-scale modeling tools and processes from a range of research and design projects. *Learning outcomes*: On successful completion of this chapter, readers will be able to: (1) explore the need for urban-scale energy and environmental modeling; (2) discuss methods of urban-scale energy and environmental modeling; (3) understand the application of modeling through case studies; and (4) appreciate the wider aspects of sustainable masterplanning.

**Keywords** Low carbon · Masterplanning · Modeling urban scale

## 3.1 Introduction

As we push forward the pace of the low carbon agenda and expand our attention from buildings to urban scale, our ability to develop models suitable for informing decision making at all stages of planning and design is essential. This chapter

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discusses work carried out at the Welsh School of Architecture, Cardiff University, on the development and application of urban-scale modeling to help us design a low carbon built environment.

The world is becoming urban. Today, around 50 % of the world's population live in cities and it is estimated that this will rise to 70 % by 2050 (United Nations World Urbanisation Prospects 2009). In the developed world, an estimated 70–80 % of the buildings that will exist in 2050 have already been built (Stunell 2011), while, in the developing world, for example, China, India, and the Middle East, they are still building at a rapid pace. By 2050, the population of the planet is predicted to increase from 6 billion today to an estimated 10–11 billion (World Population Prospects 2010). In developing countries, as people move to urban living, their carbon footprint will increase, typically by 400 % compared to rural living, as they acquire more wealth and consumer power (Li and Wang 2010). If unchecked, the energy needed to satisfy this largely city dwelling population could be many times what it is today. On the other hand, for more developed countries which have higher average national carbon footprints, urban dwellers can have a smaller carbon footprint compared to suburban and rural dwellers (Sarzynski et al. 2008), maybe up to 30–40 % less in major cities, as travel needs are reduced.

The IPCC states that we have to keep global warming below 2 °C to avoid serious impacts from climate change (IPCC 2007), which roughly means that we can put as much carbon dioxide into the atmosphere as has already been put in since industrialization began, some 150 years ago (Weaver 2008). But with current rates of development, this could take a much shorter time. The eventual aim has to be a 'zero carbon' or 'carbon neutral' planet. This means a zero carbon built environment, which implies both reducing its energy demand and decarbonizing its energy supply. This should apply not only to the operational energy for heating, cooling, etc., but also to the embodied energy, associated with the building construction and supporting infrastructures.

It is not clear precisely how much energy the built environment uses. Many sources quote that around 40–50 % (United Nations Environment Program 2007) of the world's primary energy is associated with buildings, mainly for heating, cooling, ventilating, and lighting. If mobility and other infrastructures within our cities are included, this may well rise to around 70 %. In buildings, the main uses are in areas where significant energy savings can be made without major technical difficulties. Currently, the majority of our energy is sourced from fossil fuel, however, the built environment is ideal for using renewable energy, either grid based or integrated into buildings and communities. Demand management and smart metering can have the potential for diversifying energy demand to match the variability of supply. Low carbon building design is also suitably matched to the lower grade energy supply from renewables, for example, solar thermal and ground source heat pumps.

We therefore need to design and manage our built environment based on a low carbon agenda. At urban scale, there have been a number of Eco-City initiatives, but few have been robust against financial pressures and the fast track nature of such projects. Even Masdar, probably the world's most famous 'zero carbon' city development, has had its original aims diluted, and probably justifiably so, while others, Dongtan in Shanghai, seem to have disappeared altogether. Others are being developed, but it is questionable whether they have sufficiently robust targets and evaluation procedures in order to check whether or not they meet their Eco-goals. There are a number of reasons for this apparent failure to realize Eco-City developments in practice, including: (1) lack of understanding of what sustainability is in practice; (2) lack of time to integrate sustainability into existing planning and design processes, and a reluctance to do things differently; (3) shortage of people with the appropriate knowledge and skills to engage with the low carbon agenda, and a lack of understanding of a holistic systems approach to low carbon technologies; (4) perceived high costs of doing something new and the risks associated with adopting new technologies; and (5) lack of suitable tools and procedures to plan, design, and evaluate sustainable developments, and lack of skilled people to apply tools.

Although the concept of the Eco-City is relatively new, sustainability at an individual building scale has been with us for some time. However, even at an individual building scale the results achieved in practice are rarely as predicted. For example, an evaluation of buildings designed to meet the LEED standard have shown measured energy use in practice to be often greater than predicted (Scofield 2009). Thus, when we expand the low carbon brief from building scale, to include urban-scale developments, the uncertainties escalate. For example, how do buildings interact in terms of shading and overshadowing; what are the benefits of reducing the size of supply infrastructures in response to reduced energy demand; what are the optimum densities for a development when accessibility and mobility are included? Then there is the whole issue of how much embodied energy is associated with the buildings, their services, and infrastructure support? Of course, when we consider sustainability at a community scale, the question is not just about carbon neutrality, zero waste, etc., but what the impact is on quality of life and whether people and governments will afford it. We need an evaluation process so that we can measure the outcomes against our expectations. The development of urban-scale evaluation and how it fits into a low carbon approach is the subject of this chapter.

## 3.2 Modeling at Urban Scale: Case Studies

Modeling the energy and environmental performance of individual buildings is well established. Simple models can be used to predict annual energy consumption and carbon dioxide emissions, such as the UK SAP tool used in domestic building regulations (BRE 2005). More complex models, such as HTB2 (Alexander 1996) developed at the Welsh School of Architecture, can be used to predict the hourly thermal and energy performance of buildings typically over a year. When modeling was first applied to large groups of buildings, for example, as used in the EEP (Energy and Environmental Prediction) model (Jones et al. 2000), the simpler

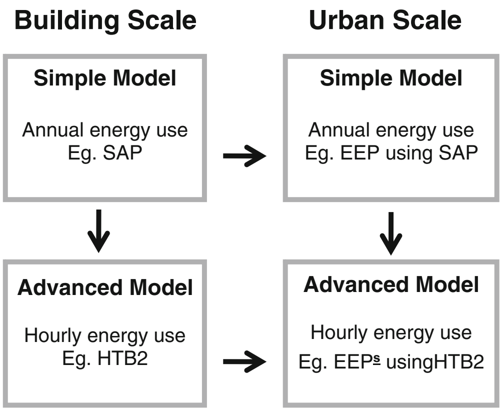


**Fig. 3.1** How modeling has developed from simple modeling of individual buildings to more advanced modeling applied to groups of buildings

energy models were often used due to computer capacity restrictions. However, nowadays, computers can be used to consider large groups of buildings at the same time using the more advanced models to predict annual hourly performance. The EEP modeling framework has been developed to use more complex models, such as HTB2. Figure 3.1 summarizes the application of computer models to individual buildings (Building Scale) and groups of buildings (Urban Scale).

Some of the more quantifiable aims of sustainability, such as environmental performance, energy use, and carbon dioxide emissions, have been the subject of previous and current design and research projects. Extending the physical modeling from individual building consideration to large scale has been considered over a number of situations covering a range of modeling techniques and parameters investigated. Some of the main studies carried out at the Welsh School of Architecture are presented in the following sections. They were often carried out in partnership with other universities or practices, and they range from neighborhood developments to whole cities. Although the focus is on a range of different environmental features, there is an emphasis on reducing energy demand and carbon dioxide emissions. They were mainly based on computer simulation; although sunlight, daylight, and wind flow scale-modeling has also been used for urban-scale environmental modeling.

### *3.2.1 Hong Kong High-Rise Residential*

The high-rise high-density residential development in Tseung Kwan O, Hong Kong (Fig. 3.2a), is typical of Hong Kong's public housing. It comprises 16, 40 story tower blocks densely located around a retail and transport hub. Each floor has 20 apartments. It is representative of the *crucifix plan* form widely used in Hong Kong. The complexity of their form, with many re-entry areas, was to allow all rooms to be naturally ventilated. There was no particular emphasis on the


**Fig. 3.2** Tseung Kwan O high-rise residential development and its model in the wind tunnel

environmental design of these buildings. A study was commissioned by the *Hong Kong Housing Authority* to assess the environmental conditions, both internal and external, for the development. The work was carried out in collaboration with the Building Services Department of the *Hong Kong Polytechnic University*. A range of environmental parameters were assessed, including, external wind flow, internal temperatures, ventilation performance, and daylighting performance (Yik et al. 2005; Jones et al. 2004a, b). The assessment used both computer simulation and physical-scale modeling, and combinations of both, for example, using measured pressure coefficients from wind tunnel modeling as boundary conditions for predicting wind-driven natural ventilation using computational fluid dynamics (CFD) airflow modeling. CFD modeling was used to simulate external wind flow, and internal air movement and ventilation rates. One of the purposes of the exercise was to provide some information on what might be appropriate modeling methods to inform the development of a residential version of HK-BEAM (Hong Kong—Building Environmental Assessment Method (Residential) (CET 1999).

The wind environment in urban situations is a crucial aspect of environmental design. It affects the external environment, in relation to *breezeways* to relieve *urban heat island* effects and pollution hotspots. It also identifies any excessive wind environments, which might impact on pedestrian comfort. It is important to understand the wind pressures on building facades in order to design for natural ventilation, for which there should be sufficient pressure differences to promote *cross-ventilation*. Analysis of the wind environment for the Tseung Kwan O development was carried out using both CFD airflow modeling and wind tunnel analysis. The wind tunnel modeling of external flows used erosion or scouring of a seeding material to provide a visual analysis of relative wind speed or gusts around a site (Jones et al. 2004b). The investigation revealed areas of accelerated wind speed of up to three times the prevailing wind speed. Figure 3.3 presents results from both CFD simulation (Fig. 3.3a) and wind tunnel tests (Fig. 3.3b).They indicate a reasonable agreement between the two methods.

The model of Tseung Kwan O, situated in the wind tunnel, is shown in Fig. 3.2b. The 'white' building has pressure sensors over the façade and it can be located anywhere on the site. The wind tunnel pressure coefficients measured over

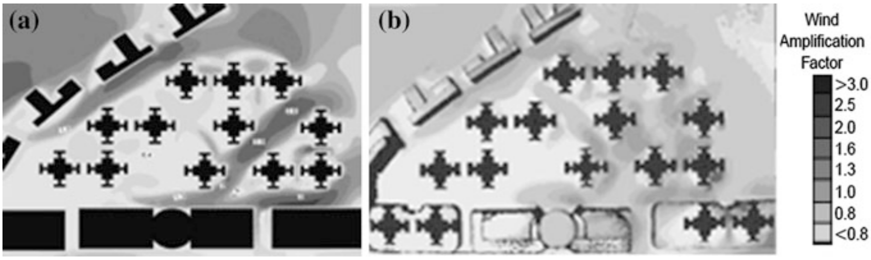


**Fig. 3.3** Wind flow at pedestrian level for **a** CFD and **b** wind tunnel analysis

the building's external facades were used to assess the ventilation performance of the individual apartments. A CFD model used these pressure coefficients to predict the internal air movement and ventilation rates for winter and summer options. For winter, trickle vents provided a basic background ventilation rate, while in summer, open windows achieved higher ventilation rates. Some example results from the study (Yik et al. 2005) are shown in Fig. 3.4 for a single block located within the development. They indicate that for most apartments, for average wind speeds, a suitable background ventilation rate of around 0.4 ac/h could be achieved in winter, while higher rates of around 4 ac/h could be achieved in summer. It is interesting to note from the results that for such a high-density development, the wind exposure at high levels appears only marginally higher than for lower levels, and the variation to wind exposure is as much related on different orientations as for different heights.

The energy load and peak internal air temperatures were simulated for typical summer conditions using the HTB2 model (Alexander 1996). The results (Fig. 3.5) indicate the sensitivity of apartments to different orientations, with the west facing apartments having higher peak temperatures (without cooling) and higher cooling loads. The façade design in practice is rarely designed to respond to orientation.

The daylight performance of the apartments was evaluated using both computer and scale modeling. A scale model (1:500) was constructed and placed in the SkyDome (Fig. 3.6a). The results indicate that much of the site is in the shadow of its neighboring buildings and that daylight levels would be low (Fig. 3.6b). Computer modeling also can be used to illustrate these effects; Ecotect (Marsh 1996) being used to estimate the level of daylight falling on the external facade (Fig. 3.6c). Again, in practice, the façade is rarely designed to account for such variations in daylight levels for different heights and orientation.

The design of high-rise developments should be more responsive to the prevailing external conditions and the interaction of buildings with each other. Figure 3.7 presents a concept design (Yik et al. 2005), based on the above analysis, to illustrate how facades can be developed to respond to height and orientation. At the top of the tower daylight and sunlight are in abundance while at the bottom some apartments 'see' very little sky. West facing apartments are at more risk from

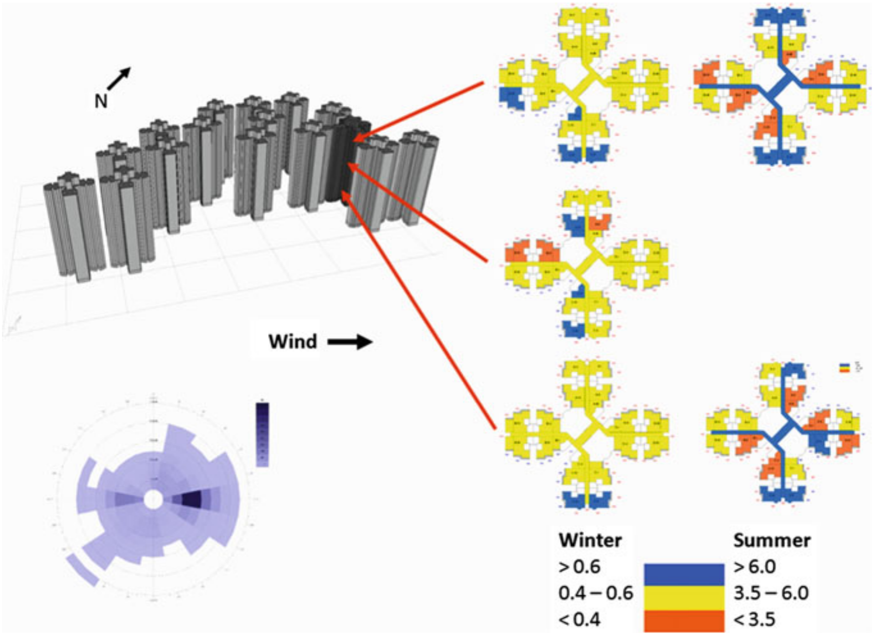


**Fig. 3.4** Winter and summer simulations of ventilation rates for a typical floor

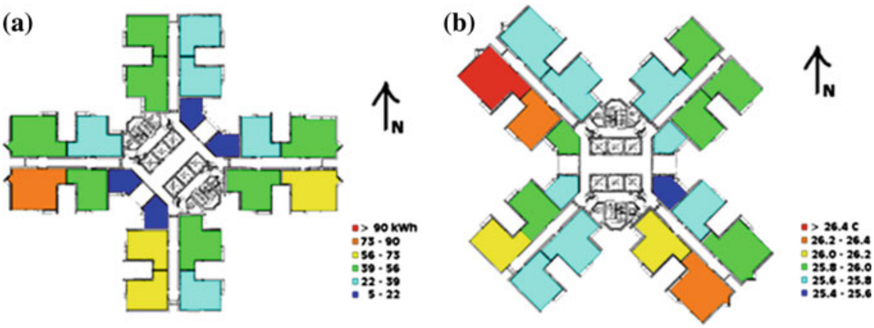


**Fig. 3.5** Typical summer cooling loads (**a**) and peak temperatures (without cooling) (**b**)

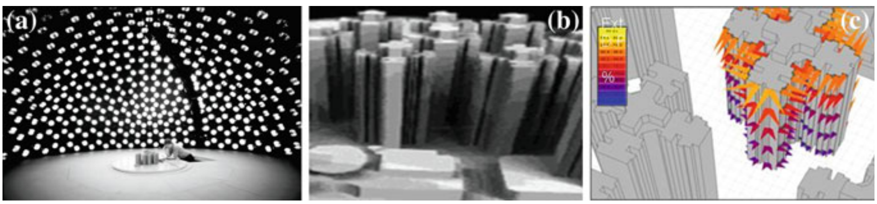


**Fig. 3.6** The 1:500 scale model of Tseung Kwan O area 59 placed in the artificial sky/heliodon (**a**), and SkyDome results (**b**), and more quantitative computer simulation results (**c**)

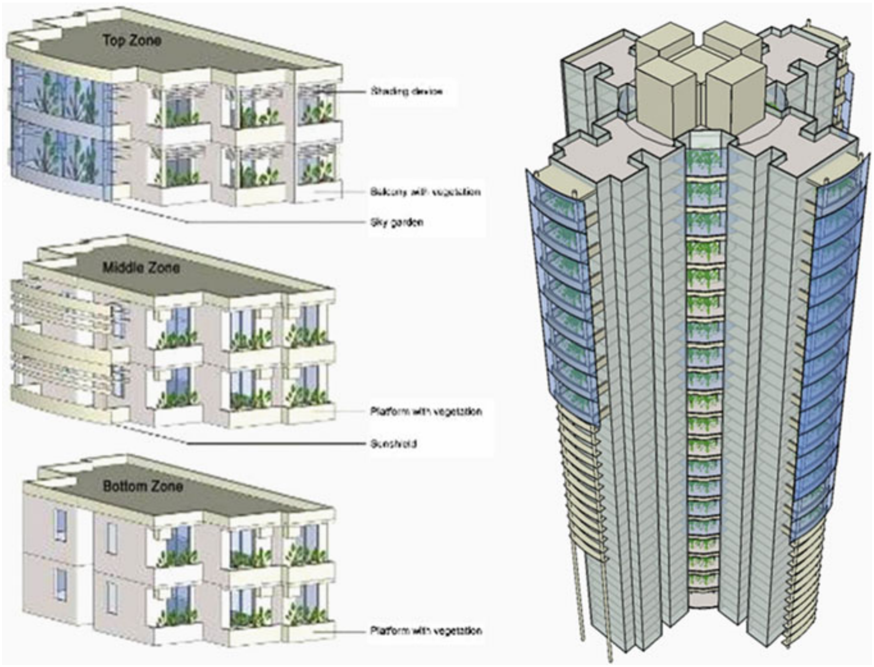


**Fig. 3.7** Concept design of high-rise tower to respond to external environmental conditions

solar heat gains; lower apartments may experience higher noise and pollution levels, which may make natural ventilation difficult.

### *3.2.2 Energy Modeling of Building Estates*

When renewable energy systems are used either at building or community scale it is useful to be able to predict the potential for renewable supply, along with the building energy demand. In this way, the supply and demand can be considered together and the balance understood, for example, in relation to electricity import and export to the grid.

A study was carried out to investigate the potential for predicting both power and heat demand for a housing estate on the same timescale and to explore the supply from renewable sources. The main aim was to use the same energy model, HTB2 (Alexander et al. 1997), to predict the energy demand for thermal and electrical power together with the energy supply from renewable systems located within the development. Also, the aim was to consider groups of buildings (houses) with varying occupancy patterns. The case study investigation was based on a group of 50 houses. Figure 3.8 illustrates the example. Building energy models use weather information, for example, solar radiation and wind speed, to

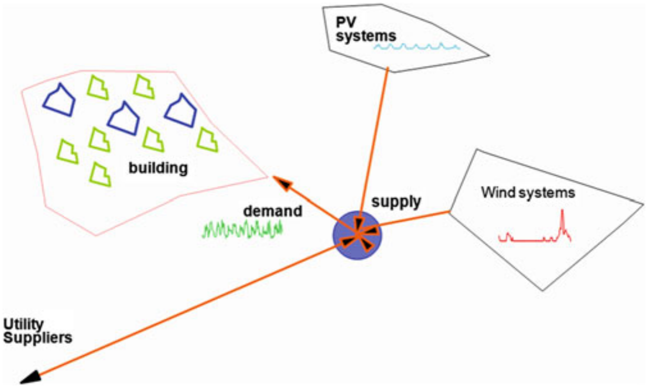


**Fig. 3.8** Site selected for application of demand and renewable supply modeling

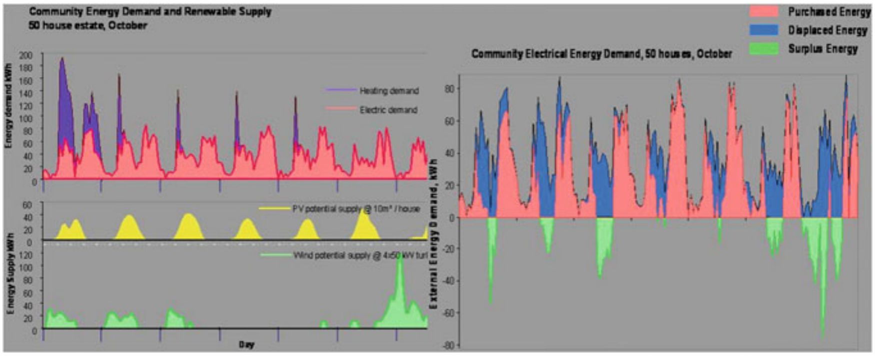


**Fig. 3.9** Results from demand and supply modeling for a site of 50 houses

predict the solar heat gains and to estimate the heat transfer at external surfaces. This information can also be used to simulate the potential energy supply from solar and wind on the same timescale, for a given system specification. In particular, the orientation and overshadowing effects that determine how much solar radiation falls on a façade can also be used to estimate how much solar radiation a solar panel would receive; a solar panel can be considered as a wall that generates energy.

Two renewable sources, namely wind turbines and solar photovoltaic, were considered for the site of 50 houses. The site was a real development, located in South Wales, therefore relating to realistic site and climate situation. The building energy model HTB2 was used to simulate the hourly variation in energy demand and supply. A random distribution of occupancy loads was used including thermostat setting, hours of use, and heat source from activity. Figure 3.9 shows results for a week's period for energy demand and supply, indicating how much energy can be supplied from the renewable systems, how much can be exported to

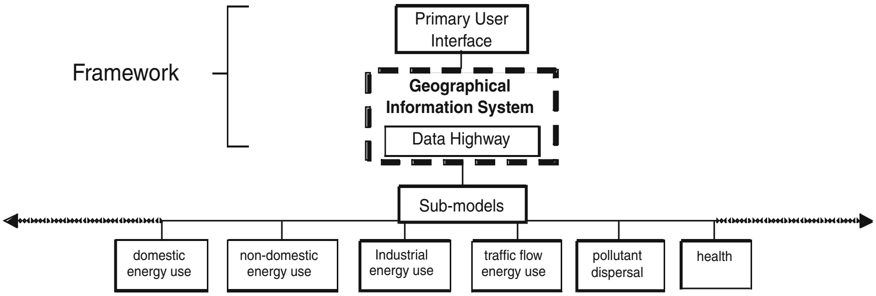


**Fig. 3.10** Structure of the EEP model

the grid, and how much needs to be purchased from the grid. This strategy has formed the basis for urban-scale energy modeling that has continued to be developed through more recent case studies.

### *3.2.3 Energy and Environmental Prediction Model for Existing Built Environments*

The Energy and Environmental Prediction (EEP) model (Jones et al. 2000) was developed to provide a framework for evaluating the performance of the existing built environment. Organizations, such as local authorities, with large numbers of buildings, need tools to help them manage energy efficiency improvement schemes, to identify where best to invest their limited resources to gain the most benefits. Initially, EEP was developed to analyze energy saving and environmental measures associated with large building stocks, alongside environmental predictions associated with transport, industry, and socioeconomic factors. EEP is a GIS-based model which contains information on all buildings within a local authority area and can, for example, quickly predict the results of carrying out programs of energy saving measures. It has submodels for predicting domestic energy use, non-domestic energy use, and traffic flow, as indicated in the framework diagram in Fig. 3.10. It has also been used to relate the built environment to health impacts (Jones et al. 2000), identifying relationships between housing and respiratory disease, accidents in the home and mental health, and neighborhood.

EEP was first applied to the existing built environment, mainly to help plan for reductions in energy and carbon dioxide emissions across large groups of buildings within a local authority area, and in particular housing. The example in Fig. 2.11a shows the thematic mapping of energy use across all houses in Neath Port Talbot DBC. Because of the large number of houses considered (about 60,000) and the range of basic types (the order of 100), a simple annual energy model was used based on the UK SAP procedure. Figure 3.11 shows the potential savings predicted from applying a package of energy saving measures (Fig. 3.11b) for

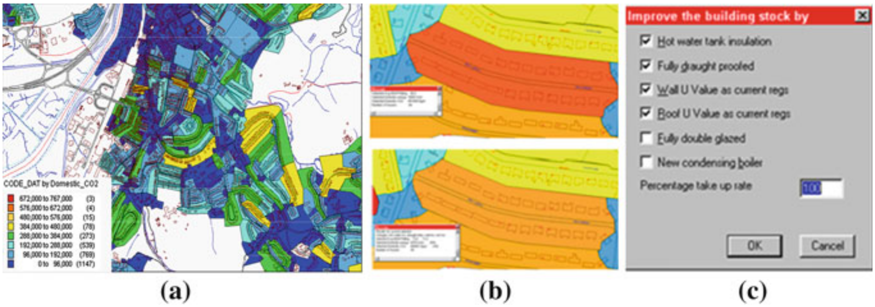


**Fig. 3.11** EEP thematic map showing carbon dioxide emissions for urban housing (**a**) and the use of EEP to identify the before and after energy performance of housing (**b**) through a menu of measures (**c**)

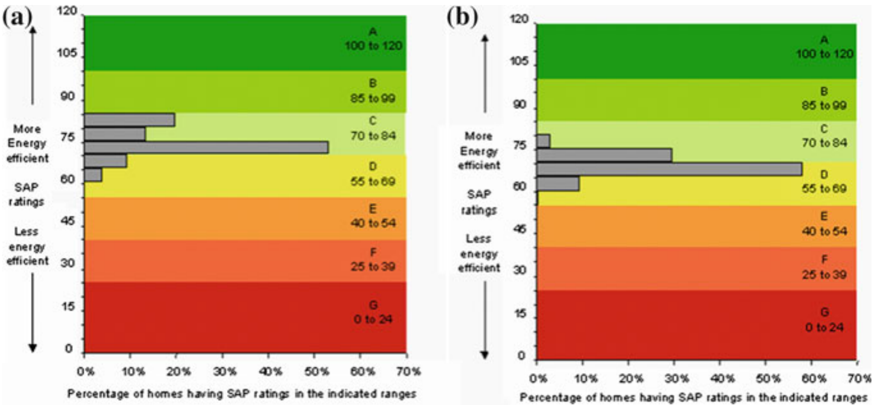


**Fig. 3.12** A SAP distribution analysis of retrofitting houses with a blanket approach (**a**) compared to selected measures (**b**)

selected groups of houses using a menu of standard measures (Fig. 3.11c). The model can then be used to determine the most appropriate package of energy saving measures for specific house types.

Surveying the buildings, in this case by a 'drive past' survey, can take a considerable amount of time; about 1– 2 years for around 60,000 houses. More recent work has developed more rapid survey methods using shape matching techniques to identify age and energy standards from Ordnance Survey maps (Lannon et al. 2007).

EEP has been used to provide an assessment of energy efficiency improvements across all Neath Port Talbot's council housing stock. Figure 2.12 compares two strategies for about 16,000 public sector houses. Blanket measures to all houses (Fig. 2.12a)resulted in an estimated cost of about £53 million, while using EEP to apply specific targeted measures for different house types, reduced estimated cost to about £23 million (Fig. 3.12b). The reduction in overall performance as

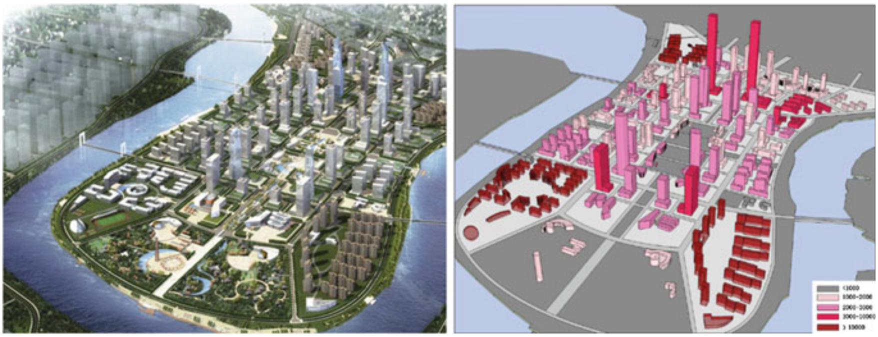

**Fig. 3.13** Concept design for the Yujiabu central business district (CBD) in Binhai, Tianjin

evaluated through SAP, can be considered to be relatively small in relation to the cost savings. Using models to inform urban-scale retrofit programs can therefore be highly cost-effective.

### *3.2.4 Yujiabu Central Business District Binhai: Energy Master-Planning for a New Development*

The Yujiabu Central Business District (CBD) in Binhai, Tianjin (Fig. 3.13), was used as a case study to explore the design of a 'green' CBD. The work was carried out in collaboration with the Tianjin University School of Architecture as part of a Leverhulme funded project (2005–2008) (Jones et al. 2008). The investigation included the early stage simulation of energy demand for heating and cooling and electrical power.

Four types of buildings were present on the development, namely, residential, commercial, educational, and offices. The energy performance simulation was carried out using HTB2. To understand possible savings on energy consumption, two comparative cases were studied for each building type, one with standard construction type and building materials and the other with optimized construction type and building materials. Thermal properties, especially U-values, of different building materials generally influence the energy efficiency design of the building envelope. At that time, U-values in China were relatively high and so there was the potential for large savings from reducing values. Energy consumption associated with heating and cooling a building is also affected by the efficiency of system performance. Appropriate heating system efficiencies (0.7 and 0.9), and the cooling COPs (1.5 and 3.0) were used for standard and optimized cases, respectively.

Figure 3.14 presents the results in EEP in the form of a thematic map of annual energy prediction for the different building type zones on the master plan. Table 3.1 indicates the potential for large energy savings and carbon dioxide

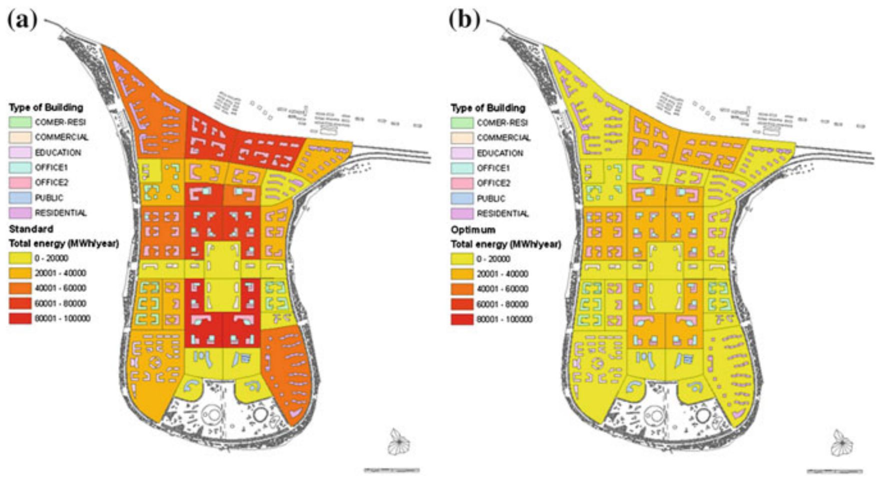


**Fig. 3.14** Thematic mapping of results for standard (**a**) and optimum (**b**) energy performance

emission reductions resulting from the optimized energy performance specification compared to the more standard values used at that time.

Although the energy modeling was carried out for the whole development, it considered buildings on their own without any influence of one building on another, for example, through overshadowing. The results, as explained above, are therefore simply an aggregation from energy use per square meter for specific building types to the whole development.

This was an example of early masterplanning stage modeling to help set low carbon targets in order to reduce carbon dioxide emissions.

### *3.2.5 Pearl Island Development, Qatar*

The Pearl Island development comprises beachfront villas, town houses and apartments, hotels, marinas, schools, and retail accommodation, all located on man-made islands in the Persian Gulf in Qatar (Pearl Island 2006). A study was carried out for the main developer, the aim of which was to provide guidelines for reducing the energy demand of the residential units by 50 % compared to the current standard (Fig. 3.15). A main driver for the study was to reduce the capacity of the energy supply infrastructure, and so reduce costs. A set of guidelines was produced for the developers to help them to achieve the 50 % energy reduction. Again, this is an example of how energy modeling can be used to inform early stage masterplanning, in this case not only to reduce operating energy costs but also to reduce the energy supply infrastructure (which will also reduce embodied energy).

**Table 3.1** Accumulated energy performance for standard and optimized cases

| Property type | Construction type | Fossil fuel energy use (kWh/m$^2$) | Electricity use (kWh/m$^2$) | Total (kWh/m$^2$) | Total $CO_2$ emission (Kg/kWh·m$^2$) |
|---|---|---|---|---|---|
| Commercial | standard | 416 | 43 | 459 | 99.7 |
| | optimum | 153 | 31 | 184 | 43.4 |
| Educational | standard | 46 | 86 | 132 | 46.8 |
| | optimum | 24 | 67 | 92 | 34.5 |
| Office | standard | 36 | 259 | 294 | 121.2 |
| | optimum | 53 | 53 | 106 | 33.5 |
| Residential | standard | 169 | 9 | 178 | 36.6 |
| | optimum | 50 | 4 | 54 | 11.5 |

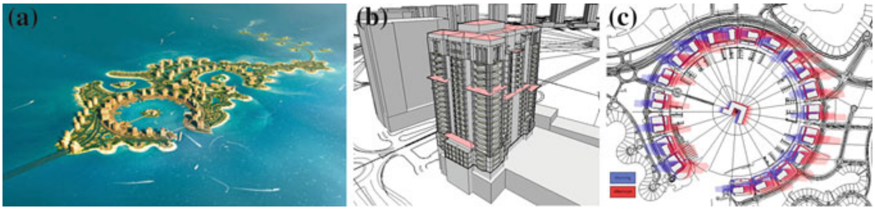


**Fig. 3.15** The Pearly Island development (**a**), typical building types (**b**), and shading analysis of site (**c**)

### *3.2.6 Ras al Khaimah: Low Carbon Master-Planning for a New City*

The Gateway City case study, in Ras al Khaimah (UAE), is a proposed new city of some 250,000 inhabitants (Jones et al. 2009). The development covers a site area of over 1,100 ha comprising an integrated city designed to service, support, and supplement the capital city of Ras Al Khaimah (RAK). The project was carried out in collaboration with ACLA Ltd, which is part of the Hyder Consultancy group.

The region experiences a hot climate with high building cooling loads. This example was based on early stage masterplanning information on building mix, height, density, and initial road layout (Fig. 3.16).

The aim of the study was to analyze the overall impact of building related energy efficiency measures and to identify potential energy savings at an early masterplanning stage that could feed into subsequent planning and design stages. The objectives of the study were: to identify the energy performance of base case requirements utilizing current and existing standards appropriate for RAK and the UAE; to develop options for optimizing energy performance and to identify variations due to orientation, overshadowing, and buildings of different height, internal gains, and construction type (in relation to thermal performance); to explore how this information, which is at a city scale, can be automated to provide guidance for individual plot planning.

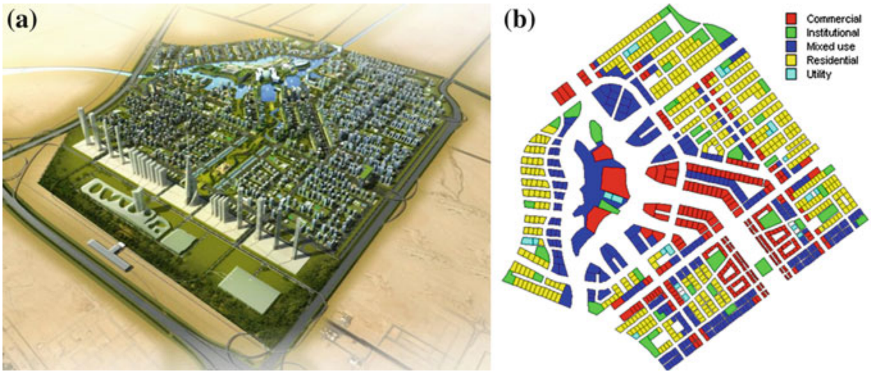


**Fig. 3.16** The proposed gateway city development (**a**) and its initial layout and building mix (**b**)

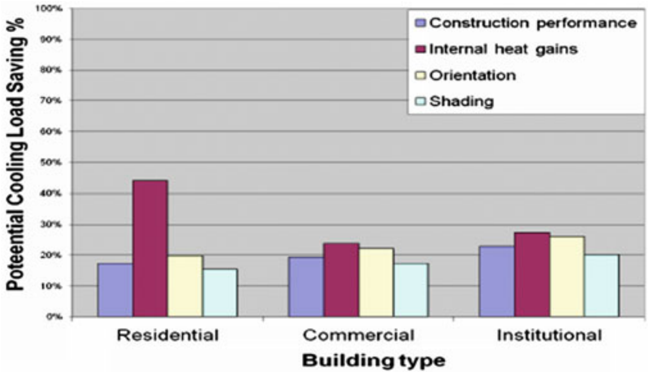


**Fig. 3.17** Range of potential cooling energy savings associated with parameter optimization

A range of simulations were carried out to test the sensitivity of the development to a range of design options at building and urban scale. Figure 3.17 shows the range of potential cooling energy savings associated with parameter optimization. Reducing internal heat gains from electrical equipment and lighting can have a major impact on cooling load. Other measures, of construction type, overshadowing and orientation of main glazed areas, can also have a significant impact (typically 15–25 %). Some of these, namely overshadowing and orientation, have to be resolved at the early planning stages.

In carrying out this work, thousands of annual hourly energy simulations were needed (using the HTB2 model), now possible through the use of high performance computers. However, the analysis of the millions of data items, and, how to interpret this to planners and designers in order to inform the process, is difficult. Figure 3.18 illustrates the use of a graphic to explain the change in cooling load associated with the facades of a building when the spacing between buildings or the height of a neighboring building is changed. As the heights and spacing of surrounding

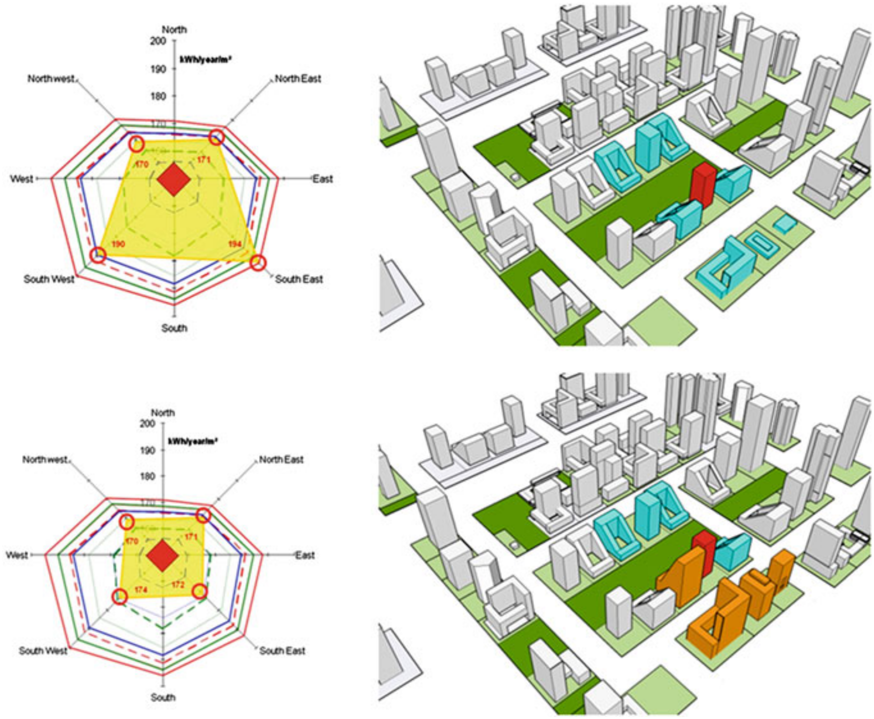


**Fig. 3.18** Impact of building overshadowing on façade energy load

buildings are changed, compared to the building in question (indicated as red in the figure), the heat gains associated with each facade of the building in question are reduced (as indicated in the diagram). This case study was used to develop urban-scale modeling to assess the energy performance of buildings within their urban context and the resulting impact of neighboring buildings. It also began to address the issue of interpreting the large data sets that are associated with detailed urban-scale modeling.

### *3.2.7 Banham: The Use of 'Sketch-Up' As a Setup Medium for Urban-Scale Energy Modeling*

Recently the EEP framework was developed with the input and output facilitated by the three-dimensional drawing package, *Google Sketchup*. The model was applied to the early stage masterplanning for the new Banham development in Chongqing (Jones 2011). It can be quickly set up to construct the development in Sketchup and the necessary data files downloaded to the building energy model HTB2 through a series of 'plug-ins'. The model predicts the operating energy of

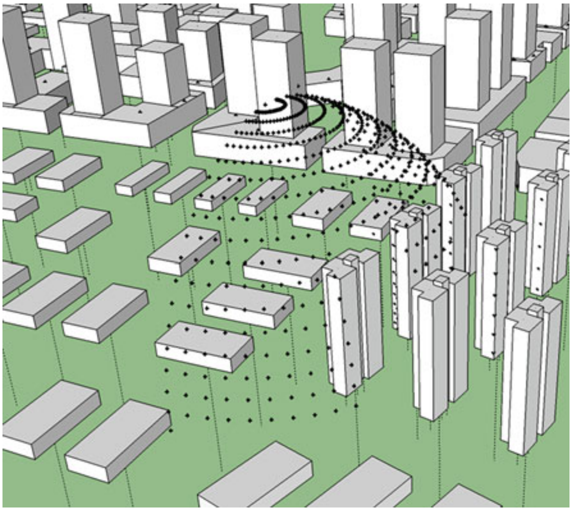

**Fig. 3.19** Solar shading mask 'plug in' in sketchup, Banham new development masterplanning simulation

the development, its embodied energy, and the potential for collecting solar energy on the building facades and roofs. The prediction method aims to include simulating the performance of both the buildings and the infrastructure. Detailed operating energy simulations are carried out to provide annual hourly results for every building in the development, in this case about 300 buildings. The model can automatically assess the interaction of buildings with each other and shading masks (Fig. 3.19) are developed for each building facade and downloaded to the energy model HTB2.

Results from the model can then be returned to Sketchup for interpretation.

### *3.2.8 Hanoi: A Megacity for the Future*

A study of a potential supercluster development for the city of Hanoi for the year 2110 was carried out in collaboration with ACLA Ltd. High-density high-rise megacities can have sustainability advantages, through efficient mobility and transport as well as good accessibility to services. Infrastructures for energy, waste, water/sewage, require less distribution which reduces carbon dioxide emissions associated with both embodied and operating energy. This reduced infrastructure energy can potentially counter the higher energy use associated with increased verticality in the built environment. The compact nature of the high-rise high-density city can potentially reduce operating energy costs for cooling and heating. The aim is to use resources efficiently and produce a good quality of life. The zero carbon approach to design aims to minimize energy demand and then generate energy from renewable sources. These renewable energy supplies could be integrated into the building design, into the neighborhood or developed outside

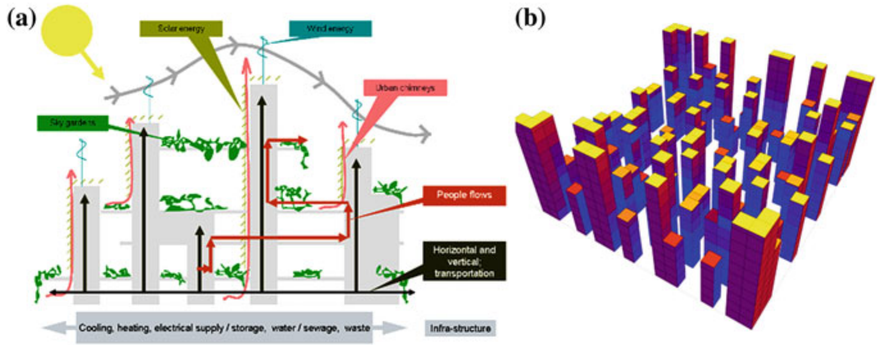


**Fig. 3.20** Aspects of super high density developments (**a**) and predicting the potential solar energy collection over building facades (**b**)

the city specifically to serve the new development. The zero carbon approach should not just be directed at buildings but it should also include transportation and other infrastructures for energy supply, waste management, water, sewage, and maintenance of green/blue structures.

This project provided some initial evaluation for the design of a supercluster of 1 million people occupying one square kilometre (Jones et al. 2010). Under current suburban density standards, a similar population would require of the order of 100 square kilometres. This vision for Hanoi 2110 potentially saves 99 % of land for other uses, providing food, leisure, material, and energy support systems for the city and conserving ecological functions. This combines to localize the ecological footprint of the city. Figure 3.21 illustrates the concept of the supercluster and Fig. 3.20 some aspects associated with its performance (Fig. 3.20a) and how urban-scale energy modeling can be used to simulate the available solar energy on building facades and roofs (Fig. 3.20b).

This example is hypothetical, but it does serve to identify environmental issues associated with the design of high-density high-rise cities, which our future simulation tools need to address. Reducing the energy demand of the city and then using renewable energy supply, reduces pollution and heat build-up. In hot countries, the planning layout with the appropriate mix of buildings with green and blue structures can introduce breezeways, urban chimney effects, and self-shading of buildings to reduce and flush out high temperatures and pollution, and provide good quality spaces for people. If cities such as Hanoi continue to grow in population, then by the end of this century they will require many superclusters in addition to their traditional urban city center. Such developments although in the future, help us focus on the modeling needs of urban developments, whether new or existing, and the parameters that need to be modeled (Fig. 3.21).

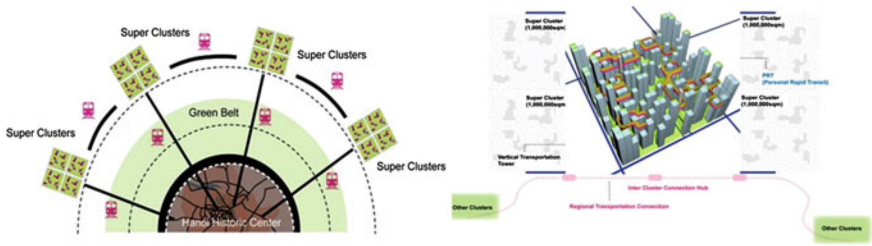


**Fig. 3.21** Hanoi supercluster city of the future

## 3.3 Developing the Evaluation Process

The above case studies have provided a wealth of experience of modeling at the urban scale of sustainability. From this, we can begin to develop a framework for sustainable urban-scale masterplanning. Such a framework should not only identify the components of masterplanning, but also clearly separate the inputs from the impact-related outcomes. Models are needed to inform the design and planning process, especially at early stages. They therefore need to cover the whole planning, design and construction process, identifying base line conditions, specifying aims, setting targets and guidelines for achieving them, and ensuring compliance through evaluation.

The process is all-important! We need to change both what we do and how we do it, probably not in a single step, but rather in a series of managed changes, learning at each stage and feeding forward into the process. For a large-scale sustainable master-plan, we can be less ambitious in the early phases, setting more easily achievable targets and concentrating more on how we might integrate sustainability into the process. It is pointless in being too ambitious in setting targets if: there is no time to develop them properly, costs are uncertain, and there is not a sufficiently skilled workforce available to carry the work out. Time, costs, skills and training needs, and the role of stakeholders, all need to be better understood. Some projects will last a long time, typically, 5–20 years and the technologies that will be available in the future do not yet exist; so there is little point in being too prescriptive about the whole program at the initial stage. We must ensure that, not only will our built environment be physically more sustainable, but it will also be socially and economically acceptable. After all, our ultimate goal should be to provide a built environment that is healthier, cleaner, and more productive, for the most efficient and effective use of resources. We need to develop a sustainability culture in the planning and design process.

In developing an evaluation process for sustainable masterplanning, the focus needs to be on outcomes at all stages of planning, design, construction, and operation. We need to set clearer goals for what we want to achieve for a specific project, how we will assess the outcomes, and identify the criteria for judging

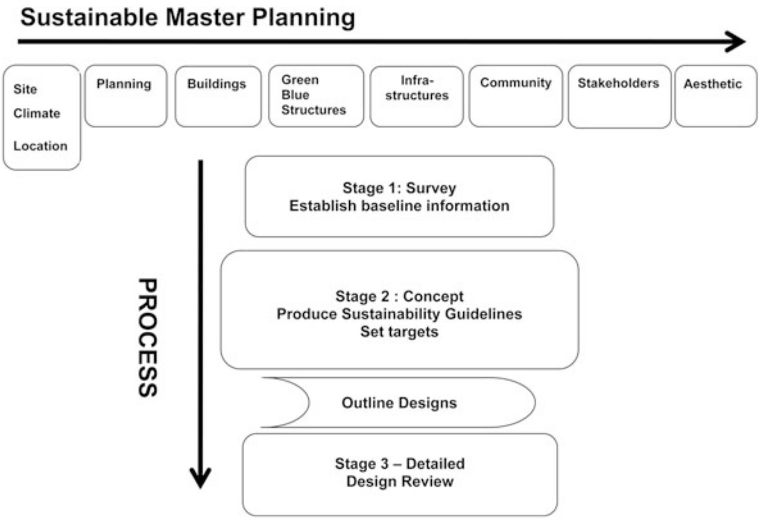


**Fig. 3.22** Framework for sustainable urban masterplanning

success. These will be different for different projects, but the generic process of setting clear aims and evaluation methods must be established.

The proposed framework (Fig. 3.22) includes the 'input' elements that should be considered in relation to sustainability and also where evaluation should be carried out from concept to detailed design review. Both quantitative and more qualitative aspects of planning and design are considered. Quantitative aspects include: details of the climate, site, the mix of buildings, their density, height, and local regulations and construction standards. It might be a new development, a retrofit of an existing development, or, a mix of new and existing buildings. New and existing infrastructures for energy supply, water, sewage, waste, landscape and land condition, and roads and transportation, are an integral part of any development. The more qualitative aspects include community, stakeholders, and the proposed esthetic of the development. The initial stages of masterplanning will need to assemble as much of these elements as possible.

The 'outcomes' of a development may be considered at global, local, and building scales. They will include, at building scale, factors such as comfort, health, productivity; at local level, outdoor air quality, accessibility to services, jobs, etc.; at a global level, carbon dioxide emissions, use of resources, etc. They should address the triple bottom line of, environment, social, and economic, together with governance issues. To be sustainable, projects should demonstrate a socioeconomic basis for their development rather than simply being property speculation without an identified socioeconomic strategy. All outcomes should be measurable and should be determined through the evaluation process.

Our current models do not generally address all the above issues, especially in a holistic way; there is much more work needed before we have a fully integrated evaluation framework for sustainable urban-scale masterplanning.

## 3.4 Conclusions

Sustainable low carbon masterplanning at urban scale is currently, in most cases, a political aspiration rather than a practical realization, with very few good practice examples. Such a 'top down' policy-driven approach does not fully appreciate the detailed practicalities and processes of sustainable planning and design at urban scale. Robust evaluation methods are essential to ensure that our low carbon sustainable understanding is developed and applied to urban-scale projects as well as at building scale. We have begun to develop and apply tools at an urban scale, but our current thinking is at the tip of the iceberg in all this. Yet, massive new projects are launched almost daily in countries such as China and the Middle East. We need to develop a more holistic and pragmatic view of how our built environment performs, and in particular how people plan, design, and use it, in order to produce tools to help us design for a higher level of sustainability. We need to consider the processes we use and how appropriate they are in relation to the low carbon agenda. This is unlikely to be achieved in a single step, but rather, through a series of manageable stages as our understanding, skills, tools, and technologies develop. We need to be clear about how we define low carbon and sustainability for a specific project, and the outcomes we expect to achieve. This chapter has presented some early stage applications of tools that could contribute to an evaluation framework. It has also presented an outline of what such a framework might look like. Without it, the Eco-City concept is unlikely to become part of mainstream masterplanning.

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# Chapter 4
# Urban Microcirculation

**Ying Jin**

**Abstract** Urban microcirculation refers to the flows of passenger and goods traffic in and around low capacity transport links in the city, principally flows for accessing homes, businesses, institutions, and intercity transport gateways. This is often the part of the transport system that received least attention and investment in the last few decades. However, urban microcirculation has become key to changing travel behavior in our quest for sustainability. Most significantly, it is in urban microcirculation that all who work on planning, design, construction, and management of the built environment must collaborate in order to achieve effective and sustainable transport solutions. This chapter outlines the main drivers for travel behavior, interactions between travel and urban land use, and a new approach to managing urban traffic to maximize economic, social, and environmental benefits. *Learning Scope*: On successful completion of this chapter, readers will be able to: (1) Understand what fundamentally drives travel behavior in the city. (2) Appreciate the basic features of urban transport systems and its interaction with activities and land use. (3) Gain basic knowledge on how to approach urban transport from the point of view of reconciling traffic, people, and activities in urban space.

**Keywords** Traffic circulation · Travel behavior · Seamless travel · Sustainable transport · Infrastructure investment · Integration of infrastructure services

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## 4.1 Introduction

Urban microcirculation refers to the flows of passenger and goods traffic in and around low capacity transport links in the city.[1] As the beginning and end of the vast majority of journeys, urban microcirculation holds the key to how people travel and deliver goods. Any efforts aiming at changing unsustainable travel behavior should therefore logically start from urban microcirculation.

However, in most countries, the reverse has been true: infrastructure spending is focused on new transport links which are predominantly outside the urban microcirculatory network. Existing urban roads are often given little attention, and in most cities there is an apparent laxity with their maintenance and use. It is not an exaggeration to say that urban microcirculation is the ‘Cinderella’ of transport in most cities today. As a result, a high degree of fragmentation persists in urban travel. The *International Transport Forum* states that transport services are *‘rarely organised along the lines of one single, seamless, door to door transport task’* (ITF 2012). This is an apt assessment as far as urban microcirculation is concerned.

There is a tantalizing analogy between urban microcirculation and human microcirculation in the medical sciences[2]: In the human body, microcirculation plays an essential role in fluid exchange between blood and tissue, delivering nutrients and removing waste; although the tiny blood vessels are invisible to the naked eye, they have a central role in the functioning of the cardiovascular system (Tuma et al. 2008). Urban microcirculation, by contrast, is the means to deliver the equivalent services with people and goods in the city. Malfunctioning of micro-circulation is debilitating to a city as it is to a human being.

However, the analogy stops quite abruptly: while major progress has been made in the last 50 years in medical microcirculation, urban microcirculation has not made much headway since the 1960s; there are key differences in the mechanisms as well: human fluids, which are mostly homogeneous, travel mostly in one-way channels within the body, whereas urban traffic is generally two-way (in spite of the drive to create one-way streets in the recent past), consisting of millions of autonomous bodies and vehicles on separately managed territories.

The most striking difference, however, is that human health can tolerate little malfunction in microcirculation, while high congestion and overcrowding of traffic in cities are generally regarded routine by policymakers, even admired from time to time as signs of prosperity (for a review, see Downs 2004, p11 onwards).

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[1] The boundary between ‘low’ and ‘high’ capacity can vary from city to city. However, as a guide the links under consideration have capacities up to those of a main street, whose capacity rarely exceeds the equivalent of 1,000 private cars per hour per traffic lane.

[2] Wiggers (1943, p 545) first points out that the real object of circulation is to maintain an adequate flow of blood in tiny vessels called capillaries. The British Microcirculation Society was founded in 1963 to ‘advance the study of the circulation of the blood and other tissue fluids especially though not exclusively in the small vessels and of matters relating thereto’ (BMS 2010).

It is thus not surprising that real progress is rare with travel behavior changing at the city scale. As a result, transport often stands out as the only sector with a rising trend in total $CO_2$ emissions in spite of continued efficiency improvements of internal combustion engines (Schäfer et al. 2009). Furthermore, the conditions of urban travel deteriorate in terms of door-to-door speed and level of service, most acutely in growing economies whose future prospects rely critically on efficient urban traffic circulation.

As with most human problems, tackling urban travel should start from a willingness to understand people's aspirations, rather than a drive to curtail them for their apparent association with undesirable effects. For most journeys, we all aspire to safe and unimpeded travel from origin to destination, with as fast a speed and as high a level of service as we can afford. This is a simple and enduring human aspiration which has proven itself repeatedly throughout human history. This is because mobility is essential for productivity and for social interaction.

The aspiration is, for instance, made obvious by how the rich and famous travel today: for certain journeys they exploit the advantage of helicopters, thus avoiding much of surface transport altogether[3]; in all cases, they enjoy carefully choreographed itineraries with short and easy transfers between travel stages. If ever there is a need to wait for a transfer, these privileged travelers are kept entertained for the duration. Delays, anxiety, and exertion within and between travel stages, i.e., the 'seams' in travel, are kept to a minimum for achieving secure, fast, and comfortable door-to-door journeys—not only for themselves, but also for their entourage and any goods to be taken (Fig. 4.1).

The development of private motorcars and trucks since the beginning of the twentieth century has raised the hopes of seamless, door-to-door travel and goods deliveries for those who are not as rich and famous. Cars and trucks have repeatedly disappointed their users on that front—first, there had been very high rates of accidents and casualties (Buchanan et al. 1963); later, congestion and gridlock have taken hold around the most popular urban destinations (Downs 2004). Adding more highways did not ease congestion in prosperous cities (SACTRA 1994), and in any case the plans for building high capacity highways within the city generally came to a halt, thanks to fears of harmful effects to local businesses, public health, the environment, and esthetics (Goodwin and Noland 2003).

Despite these ills, cars and trucks are still the closest to seamless urban travel and they have come to dominate the transport system in all major developed economies—cars and trucks account for 80 % or more of all passenger-kms and of all inland goods transport, respectively, in Britain. The major emerging economies are well on their way to producing a similar pattern, if not a more extreme one with even greater car and truck share in travel in the next few decades (Schäfer et al. 2009). Compared with other means of urban transport, cars and trucks offer far

[3] Sao Paulo has one of the highest usage of helicopters for urban travel—the city has more than 300 rooftop helipads serving more than 70,000 flights a year within the metropolitan area (Cwerner 2009).


**Fig. 4.1** A typical local street sign in England that shows competing demands for urban microcirculation

greater door-to-door convenience as well as versatility, flexibility, and speed. The predominant market share of cars and trucks forms a stark contrast to their relatively high accident rates, reliance on fossil fuels, and emission impacts.

Of course, urban microcirculation is by no means the only factor that is making it difficult to curb the dominance of car and truck use, although it is arguably the least understood. Perhaps being one of the most familiar aspects of urban living, we tend to accept urban microcirculation as it is rather than questioning it, let alone acting upon it.

We examine the extent of the problem and its significance in Sect. 2. In Sect. 3 we focus on understanding each of the main means of urban transport, which paves the way to considering the options in Sect. 4 of reconciling people, activities, and traffic, with a view to making real progress in sustainable microcirculation.[4] Conclusions are summarized in Sect. 5.

[4] Urban microcirculation and seamless travel are universal questions for practically all cities. However, by definition they require local answers which are intricately connected to parochial circumstances of each locality. With the global context in mind, this chapter will use data and examples from Britain to illustrate the discussion where a local example is needed. Britain has a long standing modern street network, superior data availability on travel and traffic, below-average urban microcirculation practices in Europe and in recent years, proactive attempts to address such problems—it is therefore a near perfect example! Those readers who are interested in testing the arguments on other countries should try to slot in their own understanding and data into the discussions and models below and see how conclusions would stand.

## 4.2 Urban Microcirculation: The Weakest Link in the Transport System?

Since the 1950s, as more people turned to cars and trucks for their travel needs, public transport has lost patronage. Meanwhile, the road space for walking and cycling became eroded. This has made it more difficult to diminish the seams on public transport journeys, as the market share of bus and urban rail travel is very sensitive to the level of patronage and the ease of pedestrian and bicycle access.

Road congestion causes delays, anxieties, and unpredictable journey times, thus introducing a 'seam' in its general sense into car and truck travel as well. However, even in congested traffic, the relative advantage of using cars and trucks door to door over other transport options tends not to diminish, although rising congestion will ultimately make cars and trucks unacceptably slow and ineffective as well.

Policy measures that aim to promote sustainable urban transport tend to focus on introducing restrictions on the use of trucks and private cars in order to tackle road congestion. For journeys beyond easy walking and cycling distance (which are the majority of passenger-kms and ton-kms), this almost invariably implies increasing the presence of seams in travel. It is not surprising that such initiatives are fiercely resisted at every turn by a 'silent majority' of businesses and motorists. The political implications of that in a democratically run city have held back the implementation of the policy measures, with few prospects of a clear breakthrough. This is compounded by worsening budget shortfalls in subsidizing public transport operations in most cities.

The inefficiency in microcirculation affects intercity as well as intracity travel, given that the vast majority of intercity trips begin and end in urban areas. From a transport user's perspective, the majority of the seams in intercity travel exist within urban areas. Microcirculation, though a minor proportion in total passenger-kms and ton-kms, is thus a pivotal issue in the development of overall transport strategy.

All the above are plain common sense, which inevitably begs questions like: why does transport investment tend to ignore urban microcirculation? Why do many governments focus on persuading travelers to shift to means of urban travel that are slower and have more seams, without effective actions to reduce the seams of travel? The answer seems to be that the seams in travel are simply too difficult to address within the realm of traditional transport policy, and policy makers have a habit to leave the most challenging problems until the end (e.g. in Britain see Headicar 2009). However, before considering how to upscale the efforts, one has to be sure that it is worth tackling this persisting problem.

### 4.2.1 How Much Does Microcirculation Matter?

Microcirculation, when functioning well, minimizes delays, anxieties, and exertion in journeys wholly within cities, and the beginnings and endings of intercity travel. In essence, it keeps the economic distance for trade and social interaction to a minimum.[5] Such benefits were already known to classical economists dating back to Adam Smith (1776) and David Ricardo (1817).

The neoclassical economist Alfred Marshall (1890) further pointed out the benefits of urban agglomeration that could arise from diminishing economic distance: i.e., opportunities to share a common pool of skilled labor, capital, materials, product markets, and a milieu for inventions. In Marshall's own words, new knowledge and know-how, often tacit and not written down, would be 'in the air', shared by those who are able to meet face to face. The congregation of businesses also creates sophisticated interdependencies between support services that are crucial to the development of major centers of commerce to this day. For instance, Cook et al. (2007) show that there are sophisticated subsector interdependencies within the financial sector within the City of London, among companies engaged in banking, investment banking, insurance, fund management, legal services, accounting, management consultancy, advertising, market research, recruitment, property management, financial printing and publishing, and the provision of electronic information; their investigations with a focus-group of these companies reveal that their 'milieu' reach no further than 500 m outside the City of London and Canary Wharf.

As cities grow, the benefits of urban agglomeration would rise so long as the opportunities to access markets and know-how rise more quickly than the economic distances between people and businesses. The studies of agglomeration effects are best summarized in the theories of the *New Economic Geography*, pioneered by, e.g., Krugman (1991) and summarized by Fujita, Krugman, and Venables (1999).

Using a theoretical framework of spatial equilibrium, the New Economic Geography explains why productivity tends to rise together with the size of urban agglomeration owing to economies of scale, increasing varieties and sophistication of goods and services available, and reductions in economic distance. In fact, the world's most successful cities, past and present, have all seen a triumph of agglomeration overcoming the effects of the economic distance: the larger the agglomeration, the more likely it is to succeed in business, technology, science, and culture (Glaeser 2010).

[5] Where the economic distance may be represented by a combination of money outlay, travel time, discomfort to people and damage to goods, etc. Anxiety, exertion and risks in unexpected delays tend to cause the travelers to perceive the travel time spent at the associated travel stages to be longer than what is the actual; for instance, time spent walking to/from and waiting for public transport services is commonly valued much more highly than time spent actually traveling (DfT 2009).

In this context, it is necessary to consider what the appropriate measure is for the size of urban agglomeration. For isolated cities far away from other settlements, the size of the city indicates its economic mass. However, in a contemporary economy, population and businesses interact across the city boundaries as well as within them, although the intensity of interaction reduces as the economic distance rises. The 'economic mass' that a city or town can command thus reflects the combined effects of the actual size of the interacting cities and the accessibility between them, as well as within each of the cities.

The most enduring measure of the economic mass was put forward by Walter Hansen (1959), taking the form:

$$M_j = \sum_i \frac{E_i}{T_{ij}^{\alpha}}$$

where $M_j$ is the economic mass of city $j$, $E_i$ is the size of the economy of each city, town, or region (including city $j$ itself) that trades with city $j$, $T_{ij}$ the prevailing door-to-door travel time for business journeys from $i$ to $j$ which can be generalized into a measure of economic distance, and $\alpha$ a distance-decay parameter to be calibrated empirically. It is apparent that a higher $E_i$ value (particularly in and around city $j$) with a lower $T_{ij}$ value would boost the economic mass.

Since Marshall (1890), although economic theories have expected that a higher $M_j$ value should be associated with a more productive city at $j$, robust empirical evidence has not been available until the 2000s. Studies in the UK suggest that doubling the economic mass would give rise to an increase in per worker productivity of 3.5 % (Rice et al. 2006).[6] The consensus view from a comprehensive review of such evidence in the developed economies, is that 'doubling city size seems to increase productivity by an amount that ranges from … roughly 5–8 %' (Rosenthal and Strange 2004). Economic mass appears to have a greater effect on productivity in the emerging economies, e.g., in the southern Chinese province of Guangdong next to Hong Kong, doubling the economic mass would give rise to an increase of per worker productivity of 9 % (Jin et al. 2012).

A rise in productivity year on year of even 3.5 % is a very substantial boost to the economy, given that the UK's average GDP growth rate over the past two decades has been little more than 2 % per year. However, doubling the economic mass is no easy matter—it would involve either doubling the volume of businesses in the metropolitan region without any increase in congestion, or halving the economic cost of all door-to-door business travel, or a combination of business

[6] The actual equation used by Rice et al. (2006) is $M_j = 10^{-6} \sum_i E_i e^{(-1.37(T_{ij}-30)/30)}$, which follows the same intuition of Hansen's equation and they found the e function gives the best statistical fit for the British data. In this case, the $T_{ij}$'s are the drive times between local authority districts in Britain.

growth coupled with falls in the economic cost of travel.[7] By the same token, agglomeration benefits can rapidly diminish if businesses start to disappear from the metropolitan region, or if congestion levels rise.

Recent developments in the sustainable transport paradigm (see review and summary in Banister 2008) tend to emphasize improvements in *reliability* rather than travel speed. Given that improvements in reliability shorten the economic distance, they could also have positive productivity benefits. However, there is no literature as yet to quantify the productivity benefits of travel-time reliability alone, as opposed to prevailing travel times.

Efforts toward increasing journey speeds have in general been central to transport policy, although the investment programs tended to focus on the trunk, intercity network. For instance, the largest current transport investment program in Britain is *High Speed 2* (HS2), a new rail line between north London and Birmingham which is expected to be extended to cities in Northern England, with an expected investment of £17bn (HS2 Ltd 2012).

The efficacy of HS2 in improving the economic mass will be significantly affected by microcirculation. The HS2 is expected to cut the in-train travel time between London and Birmingham approximately from 2 to 1.5 h, or a reduction of 25 % (HS2 Ltd 2012), which is significant on an already highly developed rail network. However, if the HS2 passengers spend on average 1 h at each end to access the HS2 terminal, buy tickets, and wait, which is not unusual for long distance rail passengers (SRA 2005), then the reduction of door-to-door travel time is only 12.5 %. Clearly, the effectiveness of HS2 is highly dependent on the seams of travel at both ends. While in-train times can be partly used for working or reading at leisure, the opportunities for doing so during station access and egress, ticket buying and waiting are far less even with the use of mobile devices. The off-train travel stages also include more seams. Therefore, cutting each minute of the off-HS2 journey time is thus likely to yield a higher reduction in the economic distance than cutting the in-train journey times.

In the past few decades, the trend in travel speed changes has been the opposite in Britain: while the speed of intercity travel has improved as a result of rail electrification and the expansion of motorways, intra-urban travel speeds have generally remained the same (e.g., in central London), or reduced (e.g., the introduction of traffic calming for road safety). Overall, the speed of car travel has reduced in recent years in spite of reductions in car traffic volumes (Headicar 2009).

[7] It should be made clear that the growth of businesses and reductions in travel times are necessary rather than sufficient conditions for productivity improvements. Other key ingredients, such as good governance of a city and attractive living conditions, are also essential.

### 4.2.2 Why Is It so Difficult to Tackle Urban Microcirculation?

To tackle urban microcirculation, it is imperative to understand where previous efforts have fizzled out and where the main barriers lie.

It is clear from the previous sections in this chapter that the main difficulties with today's microcirculation lie with the proliferation of travel stages for motorized travel and the seams therein, as labor and trade catchments expand beyond easy walking/cycle distances. The urban microcirculatory network is a fragmented one. It consists of numerous overlapping authorities, networks, institutions, management entities, nongovernmental organizations, etc., each with their own agendas. They all hold a stake in the physical space used for traffic circulation, along with the adjoining property owners, although practically no one has the right to act unfettered in reshaping it.

The seams of travel in most cases reflect the boundaries of the individual jurisdictions and entities, both between independent companies and organizations and within them (e.g., separate agencies and departments). They are therefore the very means through which the different jurisdictions establish clear responsibilities—transparency of the boundaries to the traveling public can be an effective way of enforcing those responsibilities.

Such divisions and fragmentation are nothing unusual—in fact they are prevalent in the economy. The classic response is to establish efficient markets to mediate among all jurisdictions and the users of their services. However, for urban microcirculation the markets are asymmetrical: they are effectively suppliers' markets where the users can respond to available transport services, though with few opportunities in reshaping those services.[8]

In this context, it is not surprising that policy measures to persuade users to change behavior or to reshape urban transport through individual jurisdictions have turned out to be largely ineffective. Here, the market failure lies with the government: policy intervention should have had to be through a proactive package of measures that simultaneously reshape related aspects of urban travel. In other words, in order for users to change behavior, the governments and transport operators must do that first.

Useful insights could be gleaned from the successes and failures following the publication of Buchanan et al.'s 'Traffic in Towns' (1963). The complexity of the issues involved was particularly well appreciated by Colin Buchanan, who had extensive experience in urban planning, traffic engineering, and architecture. A comprehensive package of measures was put forward to prevent gridlock in British cities, in many cases the measures proposed went well beyond traffic engineering. Their segregation principle, where different types of traffic are separated into

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[8] Even when the users are consulted, the sheer technical complexity in the urban transport system could hold back the effectiveness of their responses. That was why Henry Ford said, 'If I had asked people what they wanted, they would have said faster horses'.

different channels, has achieved major successes in improving intercity road travel, although it has failed to make much headway in addressing the speeds or environmental amenity of urban microcirculation.

### *4.2.3 Can Anything More Be Done?*

It is clear that urban microcirculation must be addressed as a system that involves not only transport services, but also is in conjunction with the rest of the built environment. There has been a ground swell in this field in recent years. For example, Headicar (2009) represents an important contribution to address the links between transport and spatial planning. Initiatives to reconcile traffic, activities, and buildings and improve public realm within certain local centers and streets (Hamilton-Ballie 2008; Gehl Architects 2009; Gehl 2010) have succeeded in improving road safety, environmental amenity, and convenience for the vast majority of users (including motorists). A common feature of all good examples has been the proactive and radical supply side interventions to reshape urban streets, transport services, and the use of the adjacent properties.

For instance, central London has now greatly improved bus services together with public realm for pedestrians, building on the positive effects of road congestion charging. As a result, significant modal shift has been achieved toward bus travel. However, more is yet to be done: the continued success of bus travel is predicated on the availability of high public transport subsidies; the ongoing problems in cycle safety and conflicts between cyclists and pedestrians show that getting people out of their cars is but a step toward sustainable travel; furthermore, average car traffic speeds are slowing down in spite of reduced car traffic volumes.

The London example also shows that the transport users have a role to play, but it is necessary for changes to be led by the supply side—users will need to experience new alternatives before they can assess the relevance to their needs. The support for central London congestion charging went up after it was implemented. This is also corroborated by the Stockholm experiment with road user charging in the city center, where citizens were asked to vote after a 6-month trial had taken place—the positive experience of the user charging scheme secured more support from the citizens than prior to the experiment, and thus enabling it to be implemented as a permanent part of managing the traffic accessing the center (Eliasson et al. 2009).

## 4.3 Understanding Urban Microcirculation as Part of an Integral Transport Network

To propose innovation, we must first understand the basic building blocks of the transport system. As standard textbooks on the nature and technical characteristics are already available (e.g., Vuchic 2007), this section serves to highlight the most relevant features of each means of transport to microcirculation.

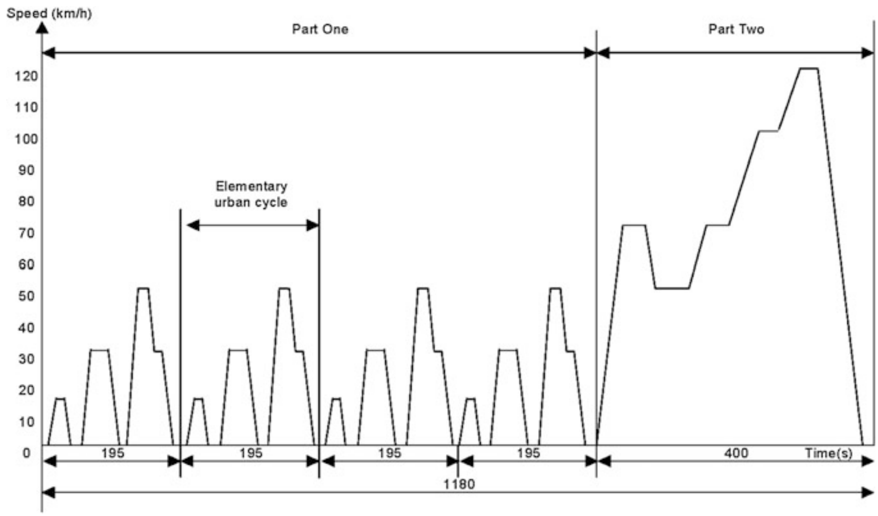


**Fig. 4.2** Standard test cycles for urban and extra-urban car driving (*Source* VCA 2011)

Walking is the most seamless way to travel, so long as the public realm makes it safe and enjoyable. However, although walking is among the most highly efficient biological movements in terms of power requirements, the physical exertion increases exponentially once the speed exceeds 3 miles (or 4.8 km) per hour. The distance range of walking is also very limited compared with labor and trade catchments in today's cities. Worldwide studies have shown that for accessing public transport, walkers have a clear preference of having rail stations within 800 m or bus stops within 200 m (Cervero 1996).

Cycling improves upon walking speeds and also increases the range, but outside recreational use, it is only used by a highly selective group—predominately young adult males working in professional jobs. Powered cycles—scooters, motorcycles, and electric bikes—further improve the speed and range. However, their use is subject to weather conditions and terrain. Most importantly, pedal cyclists are 30 times (and motorcyclists 60 times) more likely to be killed or seriously injured than car passengers. By comparison, pedestrians are 20 times more likely.

Cars (including passenger carrying vans and taxis) are the mainstay of urban traffic. They are, however, the least efficient in dense urban areas where they have to drive in a stop-start pattern. Such driving patterns are stylized in the standard EU car driving test cycles that have been in use since 2000 (Fig. 4.2).[9]

[9] In the standard car test, the urban cycle consists of a series of accelerations, steady speeds, decelerations, and idling. Maximum speed is 31 mph (50 km/h), average speed 12 mph (19 km/h) and the distance covered is 2.5 miles (4 km). The extra-urban cycle is conducted immediately following the urban cycle and consists of roughly half steady-speed driving and the remainder accelerations, decelerations, and some idling. Maximum speed is 75 mph (120 km/h), average speed is 39 mph (63 km/h) and the distance covered is 4.3 miles (7 km).

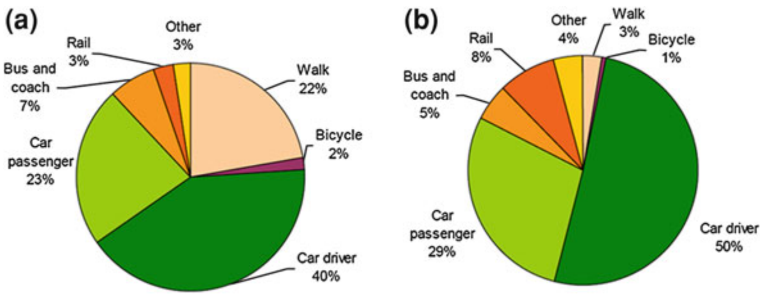


**Fig. 4.3** Market share of different means of transport in Britain. **a** Average number of trips by main mode. **b** Average distance traveling by mode (*Source* National Travel Survey 2008, p17)

Buses have the advantage, when sufficiently fully loaded with passengers, of using the road space more efficiently given the same passenger flow and travel speed. However, it is rare for public transport to offer seamless door-to-door journeys, and it is sensitive to the levels of patronage and pedestrian access. Conflict with other road users is also a sensitive issue in main urban road corridors. This issue is also present in the case of trams. Metro or underground trains have the capacity to offer much higher passenger volumes, although the capital investment and operating costs required are also much higher.

Figure 4.3 shows the current market shares of the main means of transport in Britain, where car accounts for 63 % of trips and over 80 % of passenger-kms.

The theoretical framework that can be used to explain and forecast the market share of transport modes is the *Discrete Choice Model* (McFadden 1974; Domencich and McFadden 1975). The most commonly use model form is a multinomial logit model:

$$F_{ij}^{m} = F_{ij}\left\{ e^{-\lambda(T_{ij}^{m}+\beta C_{ij}^{m}+\Omega^{m})} \Big/ \sum_{k} e^{-\lambda(T_{ij}^{k}+\beta C_{ij}^{k}+\Omega^{k})} \right\}$$

where: $F_{ij}^{m}$ is the flow volume of passengers between for a door-to-door journey from origin $i$ to destination $j$, using transport means $m$ (where $m$ is one of $k$ alternatives). $T_{ij}^{m}$ is the total door-to-door effective travel time[10] from $i$ to $j$ on $m$, $C_{ij}^{m}$ is the total monetary cost of travel. $\Omega^{m}$ is a constant representing the other influences on the choice, such as comfort, quality of service etc., which together with model parameters $\lambda$ and $\beta$ are to be estimated from observed travel behavior.

This model has been widely used in the practical assessment of travel mode choice. For example, it can be used to show the distinct travel choices for business and commuting (Fig. 4.4) between journeys that start and end within easy rail

[10] i.e. including the additional weighting of the seam effects, such as perception of bus waiting time to be twice as long as the actual lapse time.

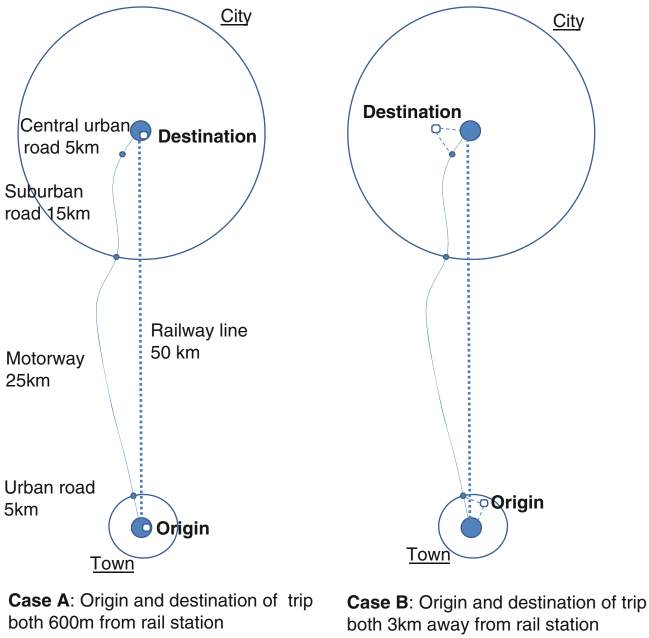


**Fig. 4.4** Comparison of journeys starting from city center and suburban locations

station catchments and journeys that start and ends in the near suburbs 3 km from the rail stations. (Left; where 90 % are by rail) (where little more than 18 % of the market share is captured by rail).

## 4.4 Reconciliation of People, Activities and Traffic

Since travel is a derived demand—the needs for travel arise from activities and the location of land use—naturally urban microcirculation is not just about coordinating the different means of transport, but a reconciliation of people, activities and traffic in invariably constrained urban spaces for traffic circulation.

### *4.4.1 Time Geography and Location Choices*

A striking feature of how people travel is the constancy of the average travel time which on average is 1–1.5 h per person per day. This is commonly found across cultures from African rural villages to highly developed economies; the constancy holds also as for people who work different number of hours (Schäfer et al. 2009). In Britain, the National Travel Survey finds that the over the years as the travel speeds rise, the average journey lengths have become longer whilst the average travel time per person per day remained stable.

Given the transport mode choice, the choice of locations can be explained and forecast using a discrete choice model, in the same vein as for transport mode choice (McFadden 1974):

$$Y_{ij} = Y_j \left\{ S_i e^{-\lambda(c_i + D_{ij} + \Omega_i)} \Big/ \sum_k S_k e^{-\lambda(c_k + D_{kj} + \Omega_k)} \right\}$$

where: $Y_{ij}$ is a flow of activity (such as commuting to work), goods or services sourced from $i$ to $j$, $S_i$ is a term that represents the size of location $i$ (given that a larger-sized location would statistically have a higher chance to be selected) among all alternatives $k$, $C_i$ is the price of production in zone $i$, $D_{ij}$ is the economic distance (i.e., transport costs, times, and any additional inconvenience), $\Omega_i$ is a constants for additional costs not included by $C_i$ and $D_{ij}$, which together with parameter $\lambda$ are to be estimated through observed choice behavior.

This theoretical framework explains, for instance, why inappropriately restraining car use may be self-defeating over time. Current urban development in Britain tends to encourage development within city centers. To curb congestion, car use is restrained and a public transport alternative is provided. However, simply being a better alternative than driving all the way into the city center or banning cars in the city center is no guarantee for long-term success: the users may decide to travel elsewhere, e.g., to new suburban centers where car travel is easier and door to door, and the goods are cheaper—this would especially be so should the amenity and attractiveness of public realm of the town center (represented by $\Omega_{i'}$ where $i'$ is the town center location) be allowed to decline.

### *4.4.2 Urban Activity Density and Its Effects*

By definition, the location of urban activity directly affects traffic circulation. To know how traffic evolves, one must know how urban land use and activities change. How urban land use and activities change over time is very difficult to foresee. Businesses and residents churn over rapidly. Globalization, technology, consumer preferences, and even chance events, all exert their influence.

Nevertheless, Duranton (2008) shows that even where there is a fast churn of industries across cities, the gross gains and losses offset each other and the overall size of a city only changes slowly. The basic patterns of land use and travel *evolve* rather than jump about, even under fast growth. This is why travel and traffic studies tend to link to broad land use patterns such as activity densities, such as measured by the number of jobs or dwellings per square km.

For instance, the 'compact city' idea in Britain promotes density pyramids, that is, 'urban areas are organized in concentric bands of density, with higher densities

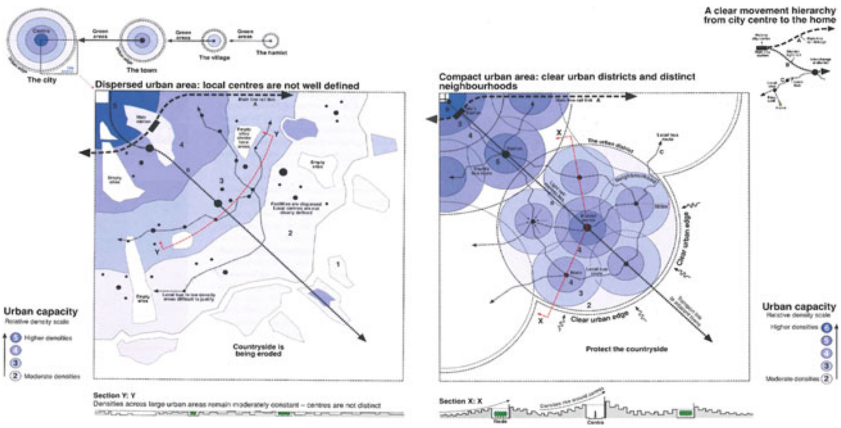


**Fig. 4.5** Trend development in Britain versus the hierarchical density pyramid proposal (*Source* Urban Task Force 1998)

around public transport nodes … and lower densities in less connected areas. The effect of this compact layout is to establish a clear urban boundary, contain urban sprawl and reduce car use' (Urban Task Force 1998, p54; see Fig. 4.5). Notably, crowding or congestion are not included as part of the objectives of the compact city approach.

The idealized compact city idea is often undermined in practice by difficulties in increasing employment and population densities around the existing public transport nodes, the high investment costs and subsidies in providing new public transport services, and the majority of the population who appear to refuse 'changing behavior' and get out of their cars. As a result, densification in Britain, by and large, takes place in an opportunistic manner on whatever urban land that has come forward for redevelopment. Even in cities where rail connections to London are attractive, such as Cambridge, the majority of developments still take place outside effective rail station catchment areas (Fig. 4.6). Some are for functional reasons (such as science and technology parks may require extensive land areas), but simple geometry implies that there is more land in the suburbs, and all being equal more sites will come forward there over time.

High density development within the city boundary (but far away from main rail or bus) may not reduce traffic congestion or improve economic mass in any appreciable way. Evidence across the UK suggests that the practice of densification since the 1990s is achieving little regarding car use; for instance, doubling residential density is associated with only 7 % reduction in per capita car use (Gordon 2008). The proponents of the compact city argue that the best examples have achieved up to a 15 % reduction in per capita car use. Even in such cases, the total amount of car use could potentially increase by 70 %, when the number of residents doubles. The compact city approach seems to be even less effective in the fast-growing South-East Britain (which includes London and its main commuting

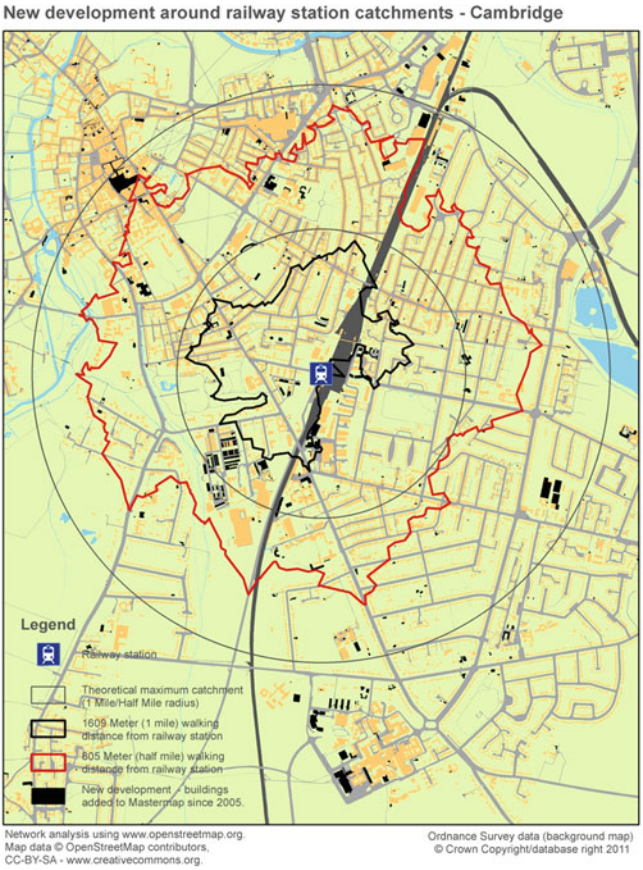


**Fig. 4.6** Cambridge: half mile and one-mile rail station catchments and footprints of new developments, 2005–2010 (*Source* Jin and Denman 2012)

catchment) in terms of total car use reduction; densification in fact increases congestion and business costs under foreseeable development scenarios to 2031 (Echenique et al. 2009).

If the level of growth is modest, the effects (either positive or negative) arising from the compact city approach may not be obvious in the short term. The surrounding neighborhoods are typically at the traditional English densities of 20–30 dwellings per hectare,[11] which means that the overall density of the area will not rise sharply. Even if the expected future growth is high, the effects of such densification will still not be immediately apparent. However, the accumulated effects of decades' worth of growth may be large on crowding and congestion. Such

[11] 1 ha = 1/100 of a sq km.

potential effects demand careful consideration, because we will want to achieve the benefits of growth without causing undue crowding or congestion.

How does density actually affect crowding and congestion? Precise data in this area are still difficult to obtain. However, we know that, broadly speaking, higher residential density is associated with longer commuting times—this should not come as a surprise, although some choose to ignore the fact for too long.

If we look inside London, we will find another pattern: the highest building densities are found in central London, but the residents there report relatively low average commuting times; the longest average commuting times are found in the boroughs of 'middling' densities (see Fig. 4.7—the London boroughs outside central London are sorted by population density).

It would be too simplistic to say that the longer commuting times all arise from the slowness of car travel, although rush hour road congestion lies at the root of the causes. In central London, the average car speeds are quite low throughout the day (and night), but the very high density makes public transport convenient and job opportunities abundant. In outer London, by contrast, car speed can be quite high until one hits a bottleneck, but commuters have to negotiate the bottlenecks, because there are not enough jobs nearby for the residents, and even if there are, specialization of skills will still require cross-commuting in the London suburbs and beyond.

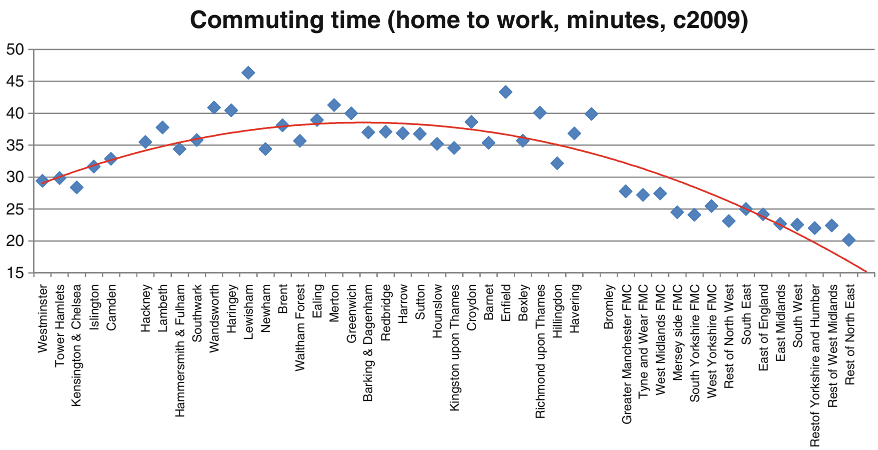


**Fig. 4.7** Average commuting times of residents versus dwelling density levels. *Note*: in the graph, five central London boroughs with the highest building density (though not necessarily the highest residential density) are presented first at the left end of the X-axis. The inner and outer London boroughs are then presented in the order of descending residential density, from Hackney (122 persons/ha) to Bromley (20 persons/ha). The rest of England is summarized toward the right end of the X-axis. The City of London is excluded here, because it has few residents and the data are unreliable. The average home to work commuting time for all London residents is 45 min and for all areas in England, 20 min. (*Data sources* Transport for London; National Travel Survey. Graph by the author)

In summary, this suggests that there may be a ‘density trap’ around middling densities; in relatively low density areas, cars dominate, but there is little congestion; in highly dense areas such as central London there are ample job opportunities nearby and convenient alternatives to car travel. Many areas in-between appear to suffer from the ills of density with few advantages of it, in particular they are dense enough to get traffic jams, but not enough to support convenient noncar travel, abundant jobs or amenities associated with very high densities. This is particularly so where there is a lack of funding for public transport or effective methods to curb car traffic.

This means that we need to think carefully about the long-term land use strategy in terms of both size and density. As the urban areas expand beyond the ordinarily range for walking and cycling, car use will be more difficult to curb. In any case, cycle traffic itself may create its own bottlenecks and conflicts with pedestrians at peak times if the road space is constrained by conservation in historic areas or, more generally the sentiment against road widening.

What we need seems to be density cones, i.e., much higher job and dwelling densities (than envisaged by the Urban Task Force 1998) in the immediate surrounds of major public transport nodes, whilst retaining the traditional English densities for the rest of urban areas without further densification. The density cones are placed according to public transport accessibility—which can be some distance from the historic centers of the cities and towns. A great deal of research suggests that people who live or work within half mile catchments of the rail or metro stations behave very differently in terms of how they travel and schedule their day-to-day behavior (work and leisure), on a proviso that they would find the area attractive to live and work in (Cervero 1996). To make such area attractive, one would need to make it dense with rich opportunities for jobs, services, and housing.[12]

### 4.4.3 A New Urban Landscape

Recent progress with modal shift from car to other means of travel in central and inner London provides useful clues in transforming urban microcirculation. This has been primarily led through *Share Space* initiatives (Hamilton-Ballie 2008), and more recently a drive to improve cyclist safety (Fig. 4.8). The efforts of transport for London in integrating urban realm improvements with traffic management, have been particularly effective on many central London sites.

[12] It should be noted here that the density cones work most effectively as employment centers rather than an area dominated by apartments. In particular, fast rail connections between metropolitan centers and suburban centers will allow the high end of business services and Research & Development jobs to distribute across the city region to take advantage of lower costs and specialism of local industry clusters.

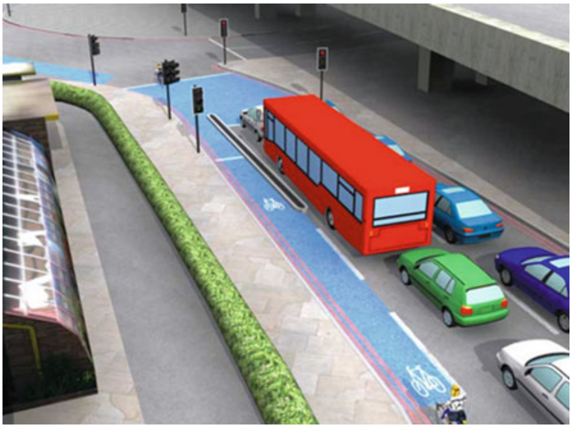

**Fig. 4.8** New design for the bow interchange, East London, to improve cyclist safety (*Source* Transport for London website; see http://www.tfl.gov.uk/corporate/projectsandschemes/22247.aspx)

However, there will be limits to incremental changes and tweaking through these measures. Share space initiatives are likely to be restricted to limited lengths and spread of roads (currently in London the exhibition road project covers less than 800 m). Furthermore, both shared space and cycle road safety measures may highlight the intense competition for road space in central urban areas. It would seem that to sustain a successful urban economy and make radical improvements in energy efficiency, a higher level strategic thinking is required, together with supply side led changes throughout the urban microcirculatory network.

The density cones development outlined above is useful to illustrate the approach. This is a proposal that could tally well with the urban growth objectives. The half-mile catchment of a station is slightly over 150 ha in size (if the streets, cycle lanes, and walkways are planned to maximize station access). If there is a way to develop the area at 500 jobs per hectare, or around half of the central London job densities, the catchment could accommodate 75,000 jobs as it is gradually built out, over, say, three or four decades. In addition, the area could accommodate around 100 units of apartments per hectare as well, and with the courtyard-type building configuration, this can all be accommodated with buildings up to 6–8 stories.

Currently, most of the surrounds of rail stations struggle even to put in a modest amount of offices and housing—some after persistent efforts over more than 20 years. What hope is there to channel more development into such areas? Protracted negotiations among groups of different visions, narrow the range of options, increase cost, and reduce flexibility down the line. These are the same difficulties that face the density pyramid approach.

A key underlying factor is the lack of consensus in the local community regarding how much development should be accommodated within the half-mile station catchments. The compromise reached between opposing interests has the danger of achieving the middling densities mentioned earlier, and diminishing flexibility in its future growth.

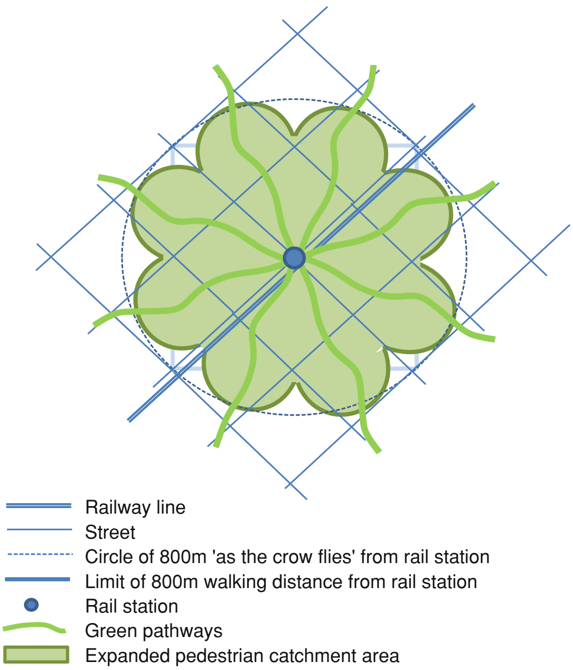


**Fig. 4.9** Transformation of public transport hubs: adding radial foot and cycle paths toward a rail station expands its 800 m catchment area from 1.28 to 1.8 sq km (*Source* Jin and Denman 2012)

Obviously, development of this nature has a long-term horizon that goes beyond 2030. However, a clear vision today will help the existing property owners (within the half-mile catchments) adapt and exploit opportunities of redevelopment at a time scale that may well be suitable to incorporate in their business or private financial plans. Proactive involvement of property owners will help to lessen the overall costs of development and any upfront finance required for acquiring land or infrastructure upgrading (van der Krabben and Needham 2008). A clear vision for the whole catchment will also help to exploit what new technology, such as hybrid fuel and intelligent cars, may have to offer in accessing very dense areas without the associated level of noise and emissions.

The ‘density cones’ will boost rail travel and create potential to absorb a significant amount of development. However, realistically speaking, the majority of the development will still take place elsewhere. In Britain, for example, over 80 % of the population live more than 1 km from a rail station (Headicar 2009). In the wider area, new ways to accommodate car use will need to be explored (Fig. 4.9).

## 4.5 Conclusion

Theories regarding urban microcirculation suggest that the flows of passenger and goods traffic in and around low capacity transport links in the city play a pivotal role in delivering sustainable transport solutions. This is, however, often the part of the transport system that received least attention and investment in the last few decades. Most significantly, it is in urban microcirculation that all who work on planning, design, construction, and management of the built environment must collaborate in order to achieve sustainable transport solutions.

This chapter shows that seamless travel is an enduring human aspiration that should be harnessed rather than curtailed in reshaping travel behavior. The microcirculatory network contains the majority of the seams of travel—intercity as well as intracity—and thus appears to be the weakest link in the transport system. Improving microcirculation is often one of the most effective ways to increase the economic mass of an urban area, thus improving its the productivity and social interaction in the local communities.

The key to making a step change in urban microcirculation is to understand why people and business behave as they do. This is supported by discrete choice models which explain the choices among the means of transport and alternative locations of land use. Because in the microcirculatory network, the population and businesses are option takers rather than option makers, any radical change must be led by supply side interventions and be followed through over decades. One of the key lessons in the implementation of the 'Compact City' proposals was that pursuing high density in new urban growth regardless of location may be counterproductive—it appears that there is a density trap where relatively high densities increase the overall levels of congestion.

Urban microcirculation should be considered as one integral system in which the creation of density cones rather than density pyramids around major public transport nodes will help reduce car use whilst cutting economic distances between main business centers. However, cars and trucks as the most convenient door-to-door modes will continue to play a dominant role—under proactive supply side interventions, they are also likely to contribute significantly to sustainable travel. This is predicated upon the reconciliation of traffic, activities, and buildings in the urban environment, particularly to reduce traffic congestion and the extent of stop-start urban driving, as well as to encourage the uptake of radically more energy efficient and low emission car engines.

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# Chapter 5
# Urban Microclimates and Simulation

**Runming Yao and Koen Steemers**

**Abstract** This chapter examines the workings of urban microclimates and looks at the associated causes and effects of the urban heat island (UHI). It also clarifies the relationship between urban form and the key climatic parameters (sun, daylight, wind, and temperature). A particular section is devoted to the concepts of UHI intensity and sky view factor (SVF); these are useful indicators for researchers in this area. The challenge of how to model urban microclimates is covered, featuring the six archetypal urban forms familiar to analysts involved in using simulation software. The latter sections address the issues of urban thermal comfort, the importance of urban ventilation; and finally what mitigating strategies can be implemented to curb negative UHI effects. *Learning outcomes*: On successful completion of this chapter, readers will be able to: (1) grasp the concept of an urban microclimate and how they affect sustainable design; (2) understand the relationship between the urban form and the climatic parameters; (3) appreciate the causes, effects, and principles underpinning the UHI effect; (4) gain insight into how to model urban microclimates; (5) know about urban thermal comfort, the importance of urban ventilation; and (6) know what common measures are taken to help mitigate UHI.

**Keywords** Microclimate · Thermal comfort · Urban heat island · Urban ventilation

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## 5.1 Introduction

Urbanization is creating some profound effects. For many rural dwellers, the promise of a better life lures them toward towns, cities, and megacities across the world. Colossal and unprecedented demographical shifts have occurred, with more than half of the world's population, since 2007, now living in or around towns and cities. Cities represent our highest concentration of energy use, and buildings alone account for the largest single proportion of energy consumption. Furthermore, urban environments impact hugely on the different facets of sustainable urban design.

A *microclimate* is defined as: 'the climate of a small area within a larger area'. An *urban* microclimate, for example, can therefore be considered as an area which is occupied by a few buildings, a village, or a small town. Unsurprisingly, urban microclimates can vary considerably within a single city and variation can be experienced from within a few meters. Variations are caused by the interaction of the urban form (e.g., building shapes, sizes, paths, roads, and vegetation) with the local climate and human activities. Such interaction has a significant impact on the overall quality of environmental conditions such as temperature, sunlight, air movement, and noise, on both indoor and outdoor conditions. Additionally, a host of other factors fall into play: urban ventilation and air pollution, energy performance of buildings, utilization of solar and wind energy in buildings, potential for passive heating and cooling measures, and urban population health and wellbeing. Subsequently, there is an urgent need to develop guidance and tools to facilitate *sustainable urban design* in order to develop *sustainable energy strategies* in urban contexts. The following sections describe how low-energy buildings are intimately linked with the urban microclimate.

## 5.2 The Urban Microclimate

Urban microclimates are both complex and dynamic. They hold many profound implications for successful urban planning and building design. Early research by Chandler (1965), Miess (1979), Landsberg (1981), and Oke (1987) generated insightful discoveries which evidenced how urban development affects the urban climate. Their work demonstrated how urban microclimates and buildings are inextricably interwoven: urban microclimates affect a building's energy consumption (and indoor environment), while buildings affect the urban microclimate.

### *5.2.1 The Urban Heat Island*

The concept of the urban heat island (UHI), or its 'effect', is characterized by warmer temperatures in built-up areas compared with its rural surroundings

(Landsberg 1981; Oke 1982). Figure 5.1 shows the causal relationship between temperature and geographical form. The causes and effects of UHIs are discussed in this section, highlighting the extent of their impact. Essentially, as the term suggests, UHIs affect thermal balances within buildings, although an extended set of impacts emerge.

The principle causation factors of the UHI effect include:

1. *Urban Morphology*
   Urban morphology describes the geometrical characteristics of built form and urban spaces: it therefore has a significant impact on urban microclimates. A *street canyon* is a valley-like space, often created by adjacent buildings. Deep street canyons with higher than average 'height-to-width' ratios (aspect ratio), reflect and absorb both short-wave and long-wave radiation. Thus, heat is magnified during daytime causing higher temperatures and cooling effects are diminished during the night;
2. *Building and Surface Materials*
   Buildings, together with hard nonporous surface materials such as concrete, brick, and asphalt, have a large heat capacity and high thermal conductivity. This means they can store heat received from both solar radiation and other heat sources in an urban area. A material's radiative properties, such as its albedo and emissivity, also have detrimental effects, as does its color. Dark surfaces tend to absorb electromagnetic radiation and warm up;
3. *Anthropogenic Heat Sources*
   Heat emitted from transportation (e.g., exhaust fumes), industrial processes, heating and air conditioning systems, and other human activities can substantially contribute to heat gains within an urban space;
4. *Local Atmospheric Pollution*
   Atmospheric pollution such as smoke, chemical, and dust particles, as well as global greenhouse gas emissions, absorbs and scatters solar radiation.

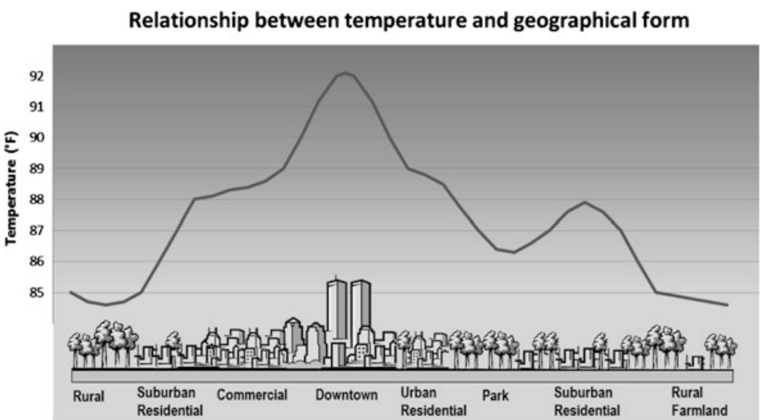



**Fig. 5.1** Graph showing the relationship between temperature and geographical form

Unfortunately, it also traps more long-wave radiation which exacerbates the greenhouse effect and increases temperatures;

5. *Urban Wind*
   Urban wind patterns tend to be more turbulent. Hence, the resulting wind speeds are slower than average, because of the urban form, their settings, and their surface 'roughness'. Heat and pollution dissipation can suffer as a consequence of reduced convection;
6. *Evapotranspiration*
   Lower levels of vegetation (e.g., trees and plants) reduce potential for evapotranspiration; that is the evaporation and plant transpiration, from the Earth's surface into the atmosphere.

The *intensity* of an UHI is defined by the maximum difference between the urban and rural temperature. Intuitively, the value of UHI intensities is greater when calculated for large-scale cities. In London, for example, the UHI effect is most intense during nighttime as opposed to during the day. Calm, clear conditions tend to increase UHI intensity.

The 'maximum heat island intensity' $T_{max}$ (also written as $T_{u\text{–}r}$ : urban–rural), can be calculated using Eq. 5.1, where, $T_{max}$ is the maximum heat island intensity, H is the street height, and W is the street width (Oke 1987).

$$T_{max} = 7.54 + 3.97 \ln (H/W) \tag{5.1}$$

It demonstrates its relationship with the building height, with respect to street width ratio (*H*/*W*). It can also be written as a function of the sky view factor ($SVF_s$) which is the relationship between the *visible area of the sky* and the *ground area covered by urban structures*.

$$T_{max} = 15.27 - 13.88\psi_s \tag{5.2}$$

Oke's Eq. (5.1) shows that the narrower a street canyon is, or the larger the height to width ratio (*H*/*W*), the greater the $T_{max}$. Oke states that the urban geometry is a fundamental control on the UHI.

Other research shows that UHI can be observed in every town and city as the most obvious climate manifestation of urbanization (Landsberg 1981). So what is the extent of its impact? Table 5.1 shows some observations which demonstrate the thermal characteristics of cities compared to their surrounding rural locations (Landsberg 1981).

**Table 5.1** Thermal implications of urbanization compared to rural environments

| Observation | Temperatures |
|---|---|
| Annual mean temperature | 0.5–3 °C warmer |
| Winter minima (average) | 1–2 °C warmer |
| Summer maxima | 1–3 °C warmer |
| Heating degree days | 10 % lower |
| Cooling degree days | 10–15 % higher |

In addition to warmer temperatures, UHI may cause secondary effects. The interplay of heat retention and emission can influence meteorological events such as changes in humidity, cloud formation, fog, and local wind patterns. Warm air rising into the atmosphere can trigger air pressure differentials which can cause precipitation in the form of light showers, and in extreme cases, storm weather conditions. Moist air from cooler surrounding regions mixes with warm 'packets' of air to help form clouds downwind. Rainy conditions frequently occur in these downwind areas compared with upwind.

It is well-known that extremes of temperature can cause a multitude of detrimental effects to human physiology and psychology. In extremes of heat, the body's thermoregulatory system is placed under significant stresses which may lead to conditions such as heat syncope, where the brain lacks sufficient blood and oxygen, thermal exhaustion, cardiovascular stress, and in worst cases, heat stroke. Strokes can subsequently lead to respiratory distress syndrome, kidney and liver failure, and blood clotting; and ultimately, fatality. Needless to say, physiological discomfort accompanies significant psychological discomfort in the form of emotional and work stress, anxiety, and mental fatigue which are all exacerbated by sleep deprivation during hot nights.

## 5.3 Modeling Urban Microclimates

Robust systems and methods for modeling internal environments of buildings are now well established; unfortunately, the same cannot be said for the analysis of external conditions around buildings. This is partly due to difficulties in defining boundary conditions appropriate to the various environmental parameters. In a similar manner, modeling such phenomena requires detailed descriptions of the urban landscape which results in heavy demands placed on input and computing capabilities. In addition, the spatial and temporal nature of dynamic interactions between a building and its urban environment creates further complexities.

It is argued that at least two levels of modeling are necessary for analyzing internal conditions using building simulation tools. Similarly, there should be two levels of modeling and analysis when investigating the external conditions (e.g., thermal, wind, and solar) when simulating urban environments. In the first instance, a preliminary level provides timely design feedback to quickly test the viability of an idea and compare multiple options at the early planning stage. Simulation results only provide 'good' indications, as modeling excludes detailed design, but a high level of accuracy is not generally required here.

More important is the *relative* accuracy; being able to assess different outcomes, say in ventilation rate, from design alterations when compared to an initial design scheme. This simplified method can help urban planners and architects to investigate urban thermal conditions with respect to various design options. The impact of building form, building height, external cladding materials, ground surfaces, and vegetation etc., can be assessed at a general level before subsequent design stages.

A limited selection of tools and models is currently available to help professionals with these issues. One such tool is *ENVI-met 3®* by Michael Bruse and his team. This software is: *'a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution of 0.5–10 meter in space and 10 seconds in time'* (ENVI-met 2011). Users can enjoy the benefit of the free software tool which is typically applied within the fields of Urban Climatology, Architecture, Building Design, or Environmental Planning. A prognostic model is used, based on laws of fluid- and thermo-dynamics and can simulate flows around buildings, heat exchange processes, turbulence, and exchange at vegetation, bioclimatology, and particle dispersion.

Another model is urban microclimate simulation model (UMsim) (Yao et al. 2011). This model applies a nodal network method to couple together thermal and airflow submodels to simulate urban microclimates. Developed as a software program, it can simulate thermal environmental parameters including surface temperatures, air temperatures, and solar radiation in urban areas. One of the program's significant features is its ability to store large quantities of data within an integrated submodel entitled digital elevation model (DEM). Particularly useful is UMsim's capability of assessing the impact of urban built forms on microclimates, in order to help create sustainable urban designs during the masterplanning stage. The coupled thermal and airflow model includes heat balance, mass balance, and pressure balance submodels. UMsim has been enhanced by integrating satellite images within the program to facilitate the simulation of large-scale urban microclimates. Figure 5.2 shows results of a computer simulation for London on 21 July 2010, covering a 60 km$^2$ area.

Figure 5.2a shows the satellite image derived from Google Earth; Fig. 5.2b shows air temperature distributions at 16:00; and Fig. 5.2c shows the ground surface temperature distribution at 16:00 in London on 21 July 2010.

Furthermore, UMsim can also perform high-resolution simulations for a small-scale neighborhood. Figure 5.3 shows the results of such a simulation for an urban microclimate in the *Elephant and Castle* area, London. Figure 5.3a shows the satellite image derived from Google Earth, Fig. 5.3b shows *air* temperature

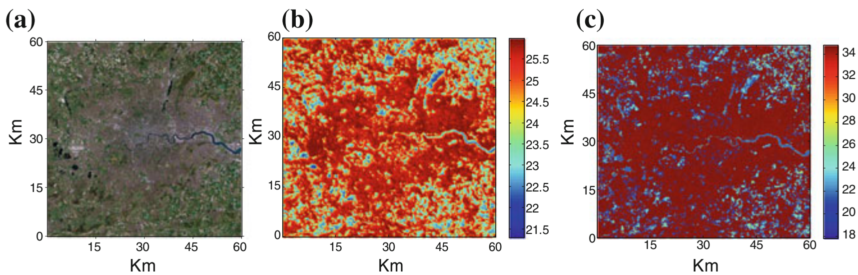



**Fig. 5.2** Urban microclimates in London (large scale), **a** Satellite image, **b** Air temperature at 16:00, and **c** surface temperature at 16:00

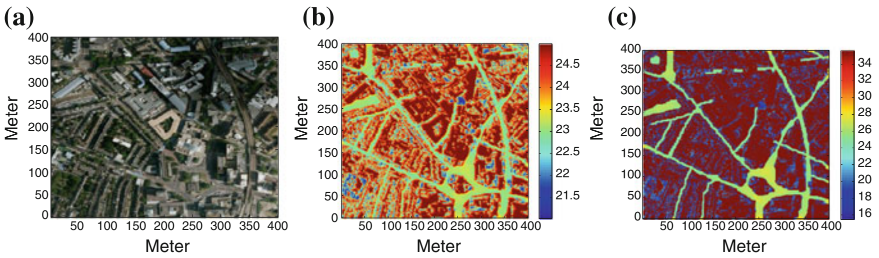



**Fig. 5.3** Urban microclimates in London (small scale), **a** Satellite image, **b** Air temperature at 16:00, and **c** Surface temperature at 16:00

distributions at 16:00 in London on 21 July 2010; and Fig. 5.3c shows *ground surface* temperature distribution for the same period.

### 5.3.1 Environmental Design Parameters

This section explores the relationship between urban form and key environmental characteristics. Its aim is to highlight the links between various urban textures and their impact on: the availability of direct solar radiation and diffuse daylight; the effects on wind and thus also airborne pollutant movement; and consequences for thermal conditions. Martin and March (1972) examined six simplified or archetypal urban forms in order to limit the complexities found in real urban textures; they were: pavilions, slabs, terraces, terrace courts, pavilion courts, and courts (Fig. 5.4). These forms are still used to examine and compare the impact of geometry alone and these forms are common to generic studies and extensively adopted (Ratti et al. 2003).

In general, these typical urban forms can be used to predict environmental performance using simplified models. Knowledge of parameters, such as the *mean surface area to volume ratio* (S/V) of a city and the average SVF, can indicate the average plan depth of buildings which can be used to assess the potential for natural ventilation, daylight conditions in the street, and the availability of solar energy.

Further still, analysis of urban form can aid designers with decisions concerning a number of environmental issues and strategies for:

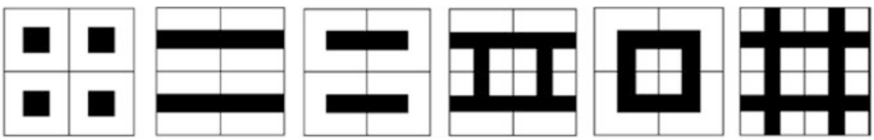


**Fig. 5.4** Archetypal urban forms; from left to right: pavilions, slabs, terraces, terrace courts, pavilion courts, and courts (*source* Ratti et al. 2003)

- Effective use of solar energy harvesting;
- The most promising positions for urban wind turbines;
- Urban areas with poor or high energy use potential;
- Managing atmospheric pollution, such as locations for waste processing plants to minimize detrimental impacts or pollution sensors to record extreme or typical conditions;
- Achieving comfort within urban spaces in the context of wind and sun, both dependent on season and climate.

Considering these attributes, the following section describes the complexities of the primary climatic factors (i.e., solar, daylight, wind, and air temperature) and how they relate to the built form shaped by our towns and cities.

#### 5.3.1.1 Solar

The quantity of solar energy received by the building envelope and at ground level is significantly influenced by the urban form; in particular, building layout, height, and surface properties which are specified by a reflectance coefficient (determined by material, color and texture). It is reported that the temperature difference between indoor and outdoor surfaces can reach 11 °C in some *urban canyons* (Georgakis and Santamouris 2006); an urban canyon being 'a canyon-like channel' formed by buildings (e.g. Michigan Avenue, Chicago).

A common parameter used to characterize the geometry of urban canyons is the SVF with notation $\psi_s$. As previously mentioned, it indicates the relationship between the visible area of the sky and the ground area covered by urban structures. Being assigned a value between 0 and 1, SVF is commonly adopted for estimating radiation fluxes in complex urban environments which essentially indicates the level of radiation that penetrates the urban canopy; therefore, providing an indication of how much radiation is absorbed by it.

Rapid developments within computing technology have vastly improved analytical methods resulting in low cost, high-resolution 3-dimensional databases of urban areas (Bradley et al. 2001; Dincer 2000; Senay and Elliott 2000; Grimmonda et al. 2001; Li et al. 2006; Matzarakis et al. 2007; Ratti and Richens 2004; Souza et al. 2003). SVF values can be calculated for any configuration of built form, facilitated by dedicated computer software. Figure 5.5 shows simulation results for the distribution of SVF using a color scale; blue to red (with red as high values) for a pavilion form with canopy heights of 10, 20, and 30 m (from left to right).

Table 5.2 shows average values for the SVF on the six archetypal buildings featured in Ratti et al.'s study (2003). In summary, analysis for hot arid and tropical climates showed that the *courtyard* outperformed the other urban shapes, but would not perform well in tropical climates. This is partly due to a limited daytime temperature variation which benefits from thermal mass are negligible and the UHI may even experience a slight increase.

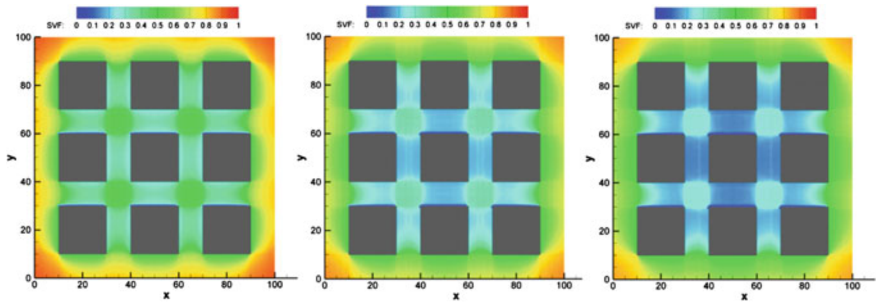


**Fig. 5.5** Simulated variation of SVFs for a pavilion urban form with canopy of 10, 20, and 30 m

**Table 5.2** Average sky view factor on archetypal building facades shown in Fig. 5.4 (Ratti et al. 2003)

| Height on façade (m) | Pavilion | Slab | Terraces | Terrace courts | Pavilion courts | Courts |
|---|---|---|---|---|---|---|
| 0 | 0.44 | 0.46 | 0.46 | 0.41 | 0.42 | 0.39 |
| 3 | 0.45 | 0.47 | 0.48 | 0.43 | 0.45 | 0.43 |
| 6 | 0.47 | 0.48 | 0.50 | 0.46 | 0.47 | 0.49 |
| 9 | 0.48 | 0.49 | 0.52 | 0.51 | 0.50 | 0.62 |
| 12 | 0.49 | 0.50 | 0.54 | 0.61 | 0.54 | |
| 15 | 0.51 | 0.52 | 0.61 | | 0.66 | |
| 18 | 0.52 | 0.54 | | | | |
| 21 | 0.53 | 0.56 | | | | |
| 24 | 0.55 | 0.60 | | | | |
| 27 | 0.57 | 0.98 | | | | |
| 30 | 0.62 | | | | | |
| 33 | 1.00 | | | | | |
| Average | 0.57 | 0.53 | 0.49 | 0.52 | 0.49 | 0.57 |

The pavilion, typically composed of tower blocks, has the highest total solar incident radiation on the building façade *and* at ground level. As expected, this form has the largest quantity of unbuilt ground area and only experiences limited shading during the day. Of course, preferred quantity of solar availability at ground level is subjective; some pedestrians may prefer high levels of sunlight whereas others prefer shaded areas, especially in hot climates.

*Courts* receive the most radiation on their building surfaces, approximately 21 % more than an urban s*lab* form, sited on a north–south axis. More than half of the total quantity of radiation is absorbed by the roof in this case, making it particularly viable for solar collection systems such as photovoltaics (PV) or solar thermal systems for hot water provision. However, courts receive less radiation on their vertical services: approximately 32 % less than towers. This significantly reduces the potential for passive solar gain. Although this may sound undesirable, this can be extremely beneficial for designing urban forms in hot climates where solar gain on building facades is unwanted. Intuitively, the orientation of urban forms has a considerable impact on solar radiation—this is particularly true for slab urban forms.

Although *pavilions* allow more solar radiation to reach ground level (24 % more than courts), in terms of solar radiation 'per square metre of open ground', courts receive a greater quantity. This can be explained by the reduction of shading experienced on unbuilt ground.

By the same token, this type of analysis also demonstrates the value of installing PV on the facades of free-standing towers or pavilions, as they receive a relatively greater amount of sunshine on their vertical facades. This renders them a more suitable form for colder climates where direct solar gains can be beneficial.

When considering public urban spaces, both *towers* and *courts* perform well, but receive different quantities of solar radiation at ground level. According to context, either urban form is suitable for climates where daylight, and particularly sunshine, is welcomed for promoting outdoor activities.

It is evident that solar radiation plays a key role in shaping urban comfort and how building service strategies are realized. A building's spatial criteria must to be established in order to develop an appropriate response. For instance, central public spaces might require more sunshine, while there may be an emphasis on active or passive solar energy systems for low-energy housing developments.

#### 5.3.1.2 Daylight

To no surprise, the availability of daylight can have a significant impact on energy efficient building design and occupant wellbeing. During the day, light negates or reduces the demand for artificial lighting. As one expects, estimating the quantity of daylight into a building is extremely helpful when planning efficient urban environments. The *luminous efficacy* of solar radiation is defined as: '*the ratio of the illuminance produced by radiation, to the radiation itself*'; or in other words, how well visible light is produced. There are three luminous efficacies: (1) global radiation; (2) direct/beam radiation; and (3) diffuse radiation (De Rosa 2008). Luminous efficacy is a useful parameter in the calculation of daylight illuminance for places with solar irradiance data (Li et al. 2008).

Engaging with computer software such as *Radiance* (LBNL 1994) is arguably one of the most effective methods for modeling real sky conditions and its effect on daylight availability in urban environments. It accounts for annual variations within the sky. Factors such as cloud cover and solar intensity are considered, thus 3D urban models can be analyzed using an appropriate 'average sky' for a particular day, season, or climate. So effective are software models that they can calculate the total irradiation or illuminance values for any surface within the model. Compagnon (2004) describes this process in some detail and demonstrates how the distribution of average illuminance can be plotted for any urban configuration. Further, simplification can be carried out to provide an overall figure for daylighting; in fact, this can also be done for larger entities like the solar system.

#### 5.3.1.3 Wind

Urban form, characterized by building density, size, height, orientation, and layout, significantly impacts on the local wind pattern and creates considerable variation in wind speeds around a building complex. Notably, there are numerous implications of urban form on the design and management of natural and hybrid ventilation and cooling strategies; this is a fundamental challenge within industry when designing effective ventilation strategies. This challenge partly exists, because such strategies are commonly based on generalized weather station wind data that have a propensity to *overestimate* the availability for natural ventilation (i.e., strategies are designed using higher wind speeds than those that occur in reality). Consequently, this results in underperforming cross, displacement, and stack ventilation systems that may have to be corrected retrospectively. Subsequent correction procedures are often disruptive, costly, and can cause excessive carbon emissions relative to the initial design assessment.

Historical field studies have clearly demonstrated that measured or actual microclimatic variables in a building complex (e.g., air temperature, wind speed, and direction), can be considerably different from the reported local and regional meteorological weather data (Turkbeyler and Yao 2009). Urban form therefore has a significant impact on urban wind patterns. Indeed, understanding the relationship between a built form and the local urban wind pattern is vitally important when designing an effective natural ventilation strategy.

Just as Oke (1988) observed, there are three types of wind flow associated with urban forms (buildings). Figures 5.6a–c illustrate these flows.

Furthermore, Fig. 5.7 shows threshold lines dividing the flow types into their three regimes as functions of the building (L/H) and canyon (*H*/*W*) geometries.

The principle characteristic determining flow type is the ratio of *building height* (H) to the *distance* (W) between building arrays, as in the case of urban street canyons. If the building ratio (*H*/*W*) along the direction of the approaching flow is less than approximately 0.30, the flow is classified as *isolated roughness flow* (where the building interacts with the approaching wind in isolation without any effects of downstream building). For a cube-shaped building, about two-thirds of the approaching mass flow-rate flows around the sidewalls, while the remaining third flows over the roof causing a turbulent '*corner flow*' effect. Another characteristic of isolated roughness flow is faster airflow along the sidewalls and over the roof which may lead to the *venturi effect.* If buildings in the lateral direction are in close proximity, this flow type often can be seen. The diverted side and roof flows eventually separate from the building surfaces creating a low-speed *wake flow*. Downstream of the building, the flow meets ground level and eventually increases to the speed of the surrounding ('original') airflow.

When the density of buildings increase in the direction of the airflow, where the ratio (*H*/*W*) of a street canyon increases (between 0.30 and 0.70), this wake flow interferes with the flow of downstream buildings. This is known as *wake interference flow*. The removal of air pollution in these situations can be adversely affected because of spacing between buildings. Finally, if the buildings are

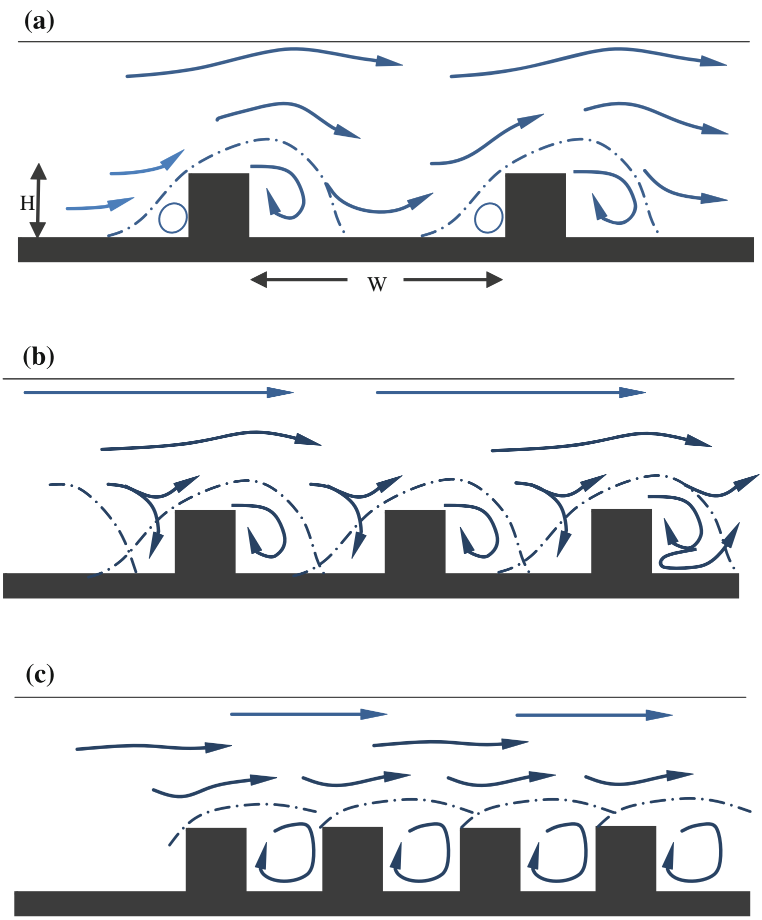



**Fig. 5.6** Three generalized flow types showing flow for an increasing building density, **a** Isolated roughness flow, **b** Wake interference flow, and **c** Skimming flow

positioned too close to one another (*H*/*W* ratio 0.7), airflow is forced to skim over the roofs of buildings downstream, and fails to remove any air pollutants between the buildings. This is known as *skimming flow*. In this case, a stable vortex appears in the street canyon between building rows. However, if the approaching wind makes an oblique angle with the axis of the street canyon, the vortex moves along the street canyon axis in a cork-screw motion (Nakamoura and Oke 1967).

Unlike a solitary street canyon, a typical and full urban layout creates different levels of airflow resistance at many point locations due to the different shapes, building sizes, and layout. As a result, the interaction between urban wind pattern and the city layout becomes more complicated than the three archetypal flows already mentioned. Therefore, it is imperative to investigate urban wind patterns in terms of different city structures and forms, such as street canyons, semienclosures,

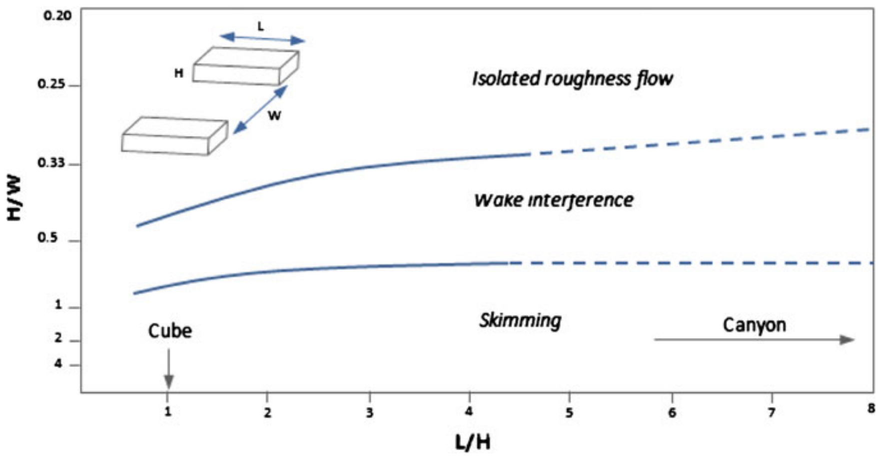



**Fig. 5.7** Threshold lines dividing the flow types into their three regimes

courtyards, and open spaces (Serteser and Ok 2009). Even then, these urban structures interact with one other's wind patterns, as they collectively shape the urban form.

When computational fluid dynamics (CFD) analysis is conducted on a building to study its wind flow characteristics, it provides detailed and spatially continuous information on the resulting urban wind pattern. This information is vital for the assessment of design and performance features, such as pedestrian comfort, façade design, positioning of air intakes and exhausts, distribution of contaminants throughout a site and its surroundings, building energy requirement for heating and cooling loads and natural ventilation.

Figure 5.8 (Turkbeyler and Yao 2009) shows an example of a CFD simulation showing simulated wind velocity vectors within a building complex.

In a similar way that solar radiation can be desirable or undesirable, wind has similar attributes. In hot climates, wind can increase passive cooling effectiveness or the dispersal of pollutants; whereas in cold climates, wind can increase heating loads. A number of conclusions can be drawn from observing wind patterns within the three generic urban forms:

- Continuous open streets aligned in the prevailing wind direction tend to be cleared of pollutants most effectively;
- For towers, the removal of pollutants is most effective if the wind direction is at 45° to the array of towers, rather than perpendicular;
- The most effective urban form that maximizes air movement is the tower;
- The least effective form that prohibits air movement is the courtyard, followed by the street form when wind direction is perpendicular to the street;
- If courts contain cleaner air (in comparison with surrounding streets), then they will *remain* less polluted. Thus, courts may be an appropriate design option assuming that no pollutants are released from within the court itself.

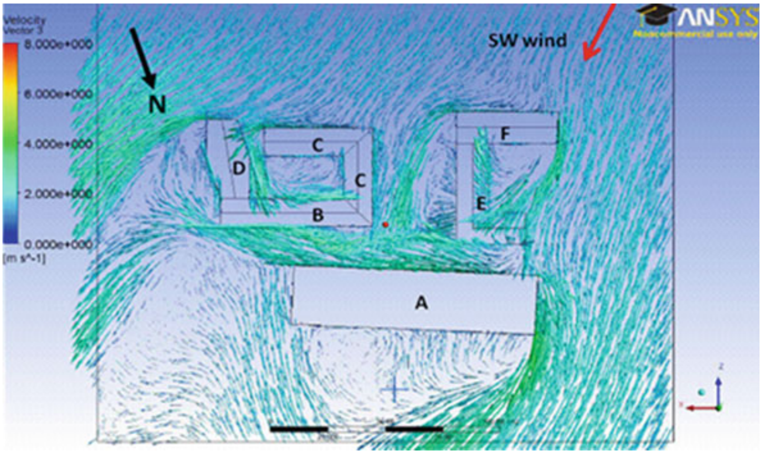



**Fig. 5.8** Wind simulation showing speed vectors in a northwesterly wind

#### 5.3.1.4 Air Temperature

As one might expect, air temperature in and around a building has a huge influence on its energy demand. Temperature is determined by a multitude of factors and as with other parameters, can be calculated. Thermal analysis of an urban neighborhood can be based either on the $T_{max}$, or on a comparison of globe temperature swing defined by Oke:

$$T_{swing} = \ln\ (1 + SVF/0.02)/0.35 \tag{5.3}$$

As Oke's correlation represents extreme conditions, the proposal is that temperature swings are a more useful metric to relate to diversity, particularly as the monitored data have demonstrated spatial effects locally. A correlation between SVF and temperature variation has been derived from the data presented above, which for urban situations with SVFs less than 0.85, is as follows (Fig. 5.9).

It is shown that the predicted peak summertime temperature variation is a function of SVF. Subsequently, this shows that the greater quantity of sky that can be seen from the ground, the greater the temperature variation.

Using computer analysis, it is possible to plot the SVFs on a pixel-by-pixel basis, allowing a degree of resolution that is appropriate for studying spatial diversity between urban spaces.

Using computer analysis, it is possible to plot the SVF on a pixel-by-pixel basis which is appropriate for studying special diversities between urban spaces. Figure 5.10 shows the SVFs for the Elephant and Castle area in London. This area has an average SVF of 0.7, which, using Oke's correlation (Eq. 5.2), creates a ($T_{max}$) of 5.5 °C. However, it is clear that the variation in SVFs across the urban area is significant, ranging from approximately 0.98 (equating to a $T_{max}$ value of 1.67 °C in the most open areas), to 0.1 in the deep courtyard spaces and narrow

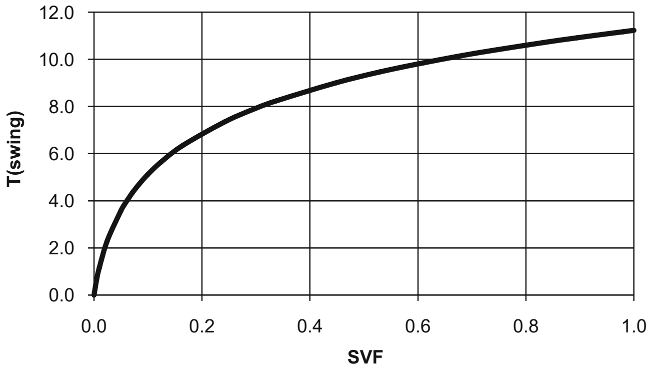
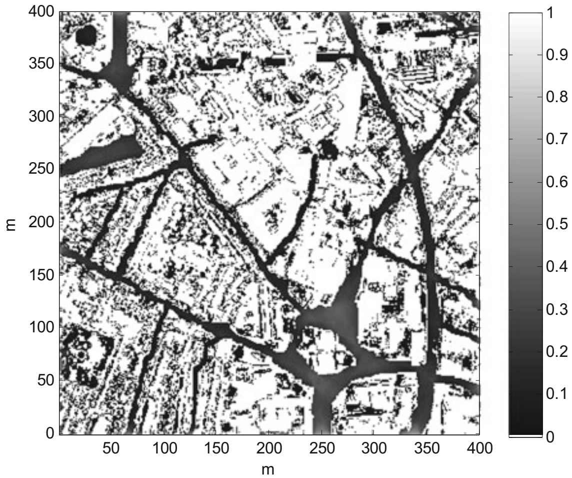



**Fig. 5.9** Relationship between temperature and SVF

**Fig. 5.10** Distribution of sky view factor for an urban site in London




alleys (where $T_{max}$ is 13.88 °C). For that range of SVFs, the corresponding range of temperature variation, using Eq. 5.3, would be between 5 and 11 °C. This means that in theory, one would expect a peak temperature difference of approximately 6 °C.

#### 5.3.1.5 Thermal Comfort

Air temperature is a major determinant of *urban comfort*. However, the over-arching term refers to the comfort that pedestrians experience in outdoor urban areas when humidity, pressure, and wind speed are also considered. Urbanization and sustainability are both driving factors which place growing importance on the overall quality of urban outdoor spaces. Needless to say, outdoor thermal comfort has been widely investigated by numerous authors in a variety of contexts throughout the world (Nunez and Oke 1977; Geros et al. 1999; Spagnolo and De Dear 2003; Cheng and Ng 2006). As our towns and cities become more populated, and sustainable practices encourage people outdoors onto cycle paths, walkways, and recreational spaces, urban street design plays an increasingly important role in ensuring that our cities are comfortable spaces to live in. Furthermore, encouraging people outdoors can deliver social benefits by increasing people's physical and mental health; even economic benefits can be realized from encouraging people into retail stores (Hakim et al. 1998; Hass-Klau 1993; Jacobs 1972; Whyte 1988). The design of the urban form is a key issue in bioclimatic urban design methodology (Oke 1988; Ali-Toudert and Bensalem 2001). The climatic parameters that determine outdoor thermal comfort have been identified in recent years (Cheng and Ng 2006; Spagnolo and De Dear 2003); however, indoor thermal comfort is still better understood to date. Nevertheless, much work has been devoted to characterizing the thermal outdoor environment; in particular, features of microclimatic urban street canyons in midlatitude locations.

Field study measurement features heavily in outdoor thermal comfort research. This has led to the development of several regression models to describe the comfort experience (Metje et al. 2008; Nagara et al. 1996; Nikolopoulou et al. 2001; Nikolopoulou and Steemers 2003; Nikolopoulou and Lykoudis 2007; Tacken 1989). Some studies have also presented questionnaire surveys to pedestrians in the street, to establish their immediate thermal sensations (Givoni et al. 2003; Tacken 1989). Givoni et al. and Tacken both developed multivariate linear regression models from such data to derive expressions for thermal sensation. Another much earlier study looked at pedestrian behavior with respect to seating on benches and the effect of solar shading on outdoor thermal comfort (Gehl 1971).

These studies use one of the most effective ways to determine comfort conditions 'on the street'. They involve carrying out surveys on pedestrians. However, this is clearly impossible where an urban project is still at the design stage. Nevertheless, extensive surveys of comfort conducted in a range of urban locations have revealed useful correlations between design parameters and comfort (Nikolopoulou and Steemers 2003); these key aspects are discussed below. Aside from physical parameters, other factors also come into play. These can be summed up as:

- physical adaptation to the environment (e.g., availability of shade, breezes, etc.);
- physical adaptation of pedestrians (e.g., clothing level, consumption of cold drinks, etc.);
- physiological adaptation (e.g., acclimatization);
- psychological adaptation (e.g., naturalness of the context, individual's expectations, and their previous experiences, length of exposure to the environment, perceived control, and effects of other stimuli).

Despite the significance of such parameters, they remain largely unquantifiable. However, interesting correlations can be found between physical parameters and perceived comfort in and outdoors (Ahmed 2003).

#### 5.3.1.6 Urban Ventilation

As urbanization takes hold of settlements throughout the world, our cityscapes become denser with urban canopies forever creeping toward the sky. In the same fashion that buildings require ventilating to reduce volatile organic compounds and toxins, so do our cities. It has been reported that a decrease in wind speed of between 1.0 and 0.3 m/s in a city center can lead to a 1.9 °C temperature increase, and outdoor thermal comfort under typical conditions requires a 1.6 m/s wind speed (Cheng and Ng 2011). Data from a meteorological station in Hong Kong showed that wind speeds at 20 meter above ground level had dwindled by about 40 % over the last 10 years due to increasing urban density (HKPD 2005). Not only is ventilation stifled at street level, but also, as one would expect, in the building themselves. A Greek study showed that the potential for natural ventilation, single-sided, and cross-ventilation for buildings in a particular urban canyon reduced by 82 and 68 %, respectively (Georgakis and Santamouris 2006). Nevertheless, the issues experienced in Hong Kong are symptomatic of what is occurring throughout the world: increased population, urban sprawl, greater densities, more traffic, and poor removal of high concentration pollutants like $NO_2$ that cause respiratory problems.

On consideration of these issues, one can begin to appreciate the importance of an urban cityscape that is purposely designed to maximize the availability for natural ventilation and pollutant removal. Simulation tools using CFD techniques are vital for analysis of these issues and to aid design which facilitates effective ventilation to curb the negative effects of poor urban ventilation. Equally important is effective urban ventilation to stave off the uncomfortable effects of the UHI, of which in the worst cases, have been responsible for occupant fatalities in extreme hot conditions.

## 5.4 Mitigation Strategies

Over time, the engineering community has developed various methods to help mitigate UHI effects. Two fundamental strategies are commonly adopted: the first is to increase vegetation coverage (Dimoudi and Nikolopoulou 2003), mainly in the form of parks, recreational spaces, and gardens in order to maximize the control of temperature rises through increasing evaporation surfaces; foliage can also capture incoming solar radiation which is essential for photosynthesis. The second is to increase surface reflectivity, by increasing the albedo, in order to reduce radiation absorption from urban surfaces.

The urban form is complex. Designers frequently encounter conflicting design principles due to seasonality and esthetics. For example, vegetation pattern (green spaces) can have both positive and negative impacts depending on seasonality. Lin et al. (2008) compared three cases and concluded that vegetation is desirable in summer for localized shading, but it creates wind breaks that reduce wind speeds which is undesirable. On the contrary, during winter, trees affect solar radiation distribution, reducing solar gains, but wind breaking effects can be beneficial.

The *H/W* ratio, also known as the *aspect ratio*, and building orientation are found to have a significant influence on reflectance variation that occurs on urban surfaces (Nunez and Oke 1977). Further studies have focused on the role of aspect ratio and street orientation for assessing the availability of solar radiation on building surfaces and on pedestrian paving (Arnfield 1990). Additional complexities are encountered due to the dynamic nature of solar radiation and pedestrian motion which can limit the number of differing situations observable.

Reflective building surfaces can be achieved simply by painting them a light color, typically white in many countries with hot climates such as Greece. Another method is to form a reflective membrane using elastomeric coatings; these have been reported to increase the albedo of commercial roofs from 10 to 70 % (Rosenfeld et al. 1995). However, both techniques are mainly applied to roofs and pavements. Indeed, shielding roofs from radiation are especially important in commercial and residential buildings where significant energy demand for cooling can be offset by reducing direct heat gains to a building. Similarly, constructing 'cool' pavements is achieved with the use of lightened colored asphalt by the inclusion of white chips. Alternatively, a light concrete covering, using Portland cement, can be used; this is called *whitetopping*.

A natural response to help designers with mitigation strategies is to develop software tools. Sailor and Dietsch (2007) created a tool called The Mitigation Impact

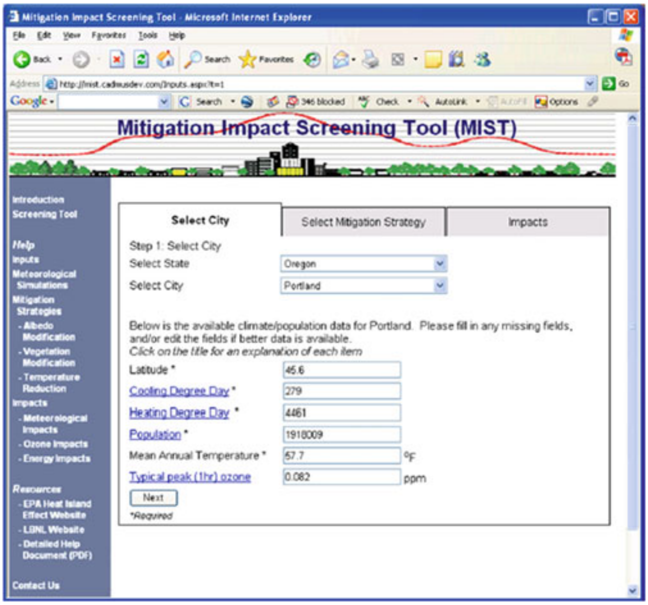



**Fig. 5.11** MIST software screenshot (http://www.heatislandmitigationtool.com/Introduction.aspx)

Screening Tool (MIST) developed by the United State Environmental Protection Agency, a screenshot is shown in Fig. 5.11. The tool can be used to assess the urban climate, air quality, and energy consumption of over 170 cities and users can specify the surface reflectance and vegetation cover in their simulations.

## 5.5 Conclusion

This chapter introduces the concept of the urban microclimate and the UHI. It delves into the causes and effects of such a phenomena and what can be implemented to reduce its impact. Many authors have contributed to the understanding of how urban form and climate interact with one another, and how this interaction influences the UHI effect. In addition, such research has illuminated technical strategies to help cope with the effect and highlights what kind of tools we have in our armory.

The studies mentioned in this chapter, together with the work of other authors in this field, suggest that in order to limit the impacts of the heat island effect, urban development should:

- limit the overall urban scale (defined here in terms of population size, but the heat island can equally be related to the physical extent of urbanization);
- reduce reliance on private transport, mechanical systems, and other anthropogenic factors which increase local pollution and exacerbate the heat island effect;
- introduce an appropriate level of vegetation and porous ground surfaces to increase evaporative cooling;
- increase the urban albedo by constructing with light-colored surfaces to reflect solar radiation;
- increase the 'porosity' of the urban fabric to permit greater urban air movement which helps to dissipate heat and urban pollutants.

A look into how models are used to analyze microclimates underlines the need for a careful and considered approach for planning our sustainable cities of the future. Not only do we have to consider the primary effects from the local climate (e.g., solar, daylight, wind, and temperature), but also secondary issues that reveal themselves through occupant wellbeing and in weather systems further afield. Finally, this chapter concludes by highlighting the importance of urban thermal comfort, the need for effective urban ventilation, and what can be implemented to alleviate the negative effects of the UHI. Sustainable design will play an increasingly important role in delivering low-energy urban environments which are healthier places to live in.

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# Chapter 6
# Urban Acoustic Environment

**Jian Kang**

**Abstract** Acoustic environment is an important aspect of the overall urban environment, and in the last decade or so, major new developments have come to light in the field in terms of research and practice. Urban acoustic environment covers a wide range of issues, of which this chapter discusses some key factors. Urban noise evaluation and regulation are first introduced. Various prediction and simulation methods for sound propagation in micro-scale urban areas as well as techniques for large-scale urban noise-mapping are then presented. A series of noise control measures and design methods relating to the built environment are also described. Finally, soundscape is introduced, which is a major step further from simply reducing urban noise level. *Learning Scope*: On successful completion of this chapter, readers will be able to: (1) Understand sound environment in urban areas in terms of noise evaluation and regulation (2) Have familiarity with sound propagation simulation and prediction, as well as noise control techniques and (3) Gain basic knowledge in urban soundscapes.

**Keywords** Acoustic environment · Noise prediction · Regulation · Sound propagation · Urban soundscape

## 6.1 Introduction

The acoustic backdrop to the built environment, or its *soundscape*, plays an important role in creating healthy places where people live and work. Much work has been devoted to measuring and assessing the characteristics of our urban

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environment in order to develop international standards whereby to gage the effectiveness of urban planning in delivering safe, pleasant, and harmonious spaces. Our perception of noise is governed by many factors, and the tools and mathematical models in which sound prediction are based, are now rigorously sufficient to use in a multitude of areas where soundscape analysis empowers designers. This chapter delves into how the acoustic environment can be evaluated, adapted and purposely designed to minimize the negative impacts of noise and maximize the positive attributes of sound, benefitting our wellbeing; from individuals to communities.

## 6.2 Urban Noise Evaluation and Regulation

Environmental noise is unwanted or harmful sound. This is commonly caused by human activities including road traffic, railways, air transport, industry, recreation, and construction; and perceived in the near domestic environment such as residential areas, public spaces, and community environments like schools. This section briefly discusses evaluation of urban noise (Sect. 6.2.1), noise indicators (Sect. 6.2.2), and typical noise standards/regulations (Sect. 6.2.3) (Kang 2006).

### *6.2.1 Factors Affecting the Evaluation of Urban Noise*

The evaluation of sound, measured in decibels (dB), is a complex task which has many facets including acoustic, physical, social, psychological, economic, and behavior factors (Kang 2006).

In terms of acoustic and physical facet, the overall sound level is an important factor for subjective evaluation. It is suggested that annoyance caused by daytime traffic noise, can be categorized into three noise levels: <55 dBA, no annoyance; 55–60 dBA, moderate annoyance; and >65 dBA, definite annoyance (Lambert et al. 1984). This is where dBA is calculated using the A-weighting system, which is employed by arithmetically adding a weighting value at each frequency band to the measured sound pressure level (SPL) in dB, and the resulting frequency band SPL is then added (logarithmic method) to provide a single dBA value. It is also important to consider noise characteristics within the spectrum. For example, greater tonal components can increase annoyance, and there is increasing evidence showing that low frequency components also play an important role in causing annoyance. It is suggested that increasing the number of acoustic events by a factor of 10, causes a similar increase in annoyance, when compared with increasing the average peak level by 5 dB (Fields 1984). Situational variables such as relatively long-term changes in noise exposure are also important. In many cases, a progressive drop of several dB over a long period of time often goes unnoticed. Other factors which affect annoyance include: regularity of events, maximum sound level, rise time, duration of occasional events, spectral distribution of energy, and number and duration of quiet periods.

Social, psychological, economic, and behavior factors also play a key role in annoyance evaluation. Aspects within people's attitude can influence annoyance, including fear, cause of noise, sensitivity to noise, activity, perception of the neighborhood, and the global perception of the environment. The effects of various demographic factors on sound evaluation have also been intensively studied. Inconclusive, evidence revolves around a person's age, whereas most studies seem to suggest that gender is not statistically significant. Other possible influential factors include marital status, family size, education level, income, economic status, and income, general state of health, house size/type, and occupancy (i.e., owning or renting). Noise experience, including prolonged exposure to commercial or industrial noise, can affect residential noise annoyance together with people's sleep patterns. The period of residence appears insignificant when evaluating acoustic annoyance, whereas 'hours spent in the home' is significant. Occupant behavior and habits, including: opening and closing of windows, use of sleeping pills, enjoying balconies or gardens, home sound proofing, and unoccupied weekend periods, are all other important aspects which can affect annoyance. The economic effects of noise have been studied, especially from the viewpoint of compensation, payable to home owners experiencing depreciation in property value attributed to noise, among other physical factors. Based on several case studies, initial relationships have been established between dB increase and house price decrease, with corresponding noise thresholds (cut-off noise level), although considerable further work is still needed.

Seasonality and the time of day can also influence annoyance evaluation. It was found that noise annoyance was greater in summer than in winter, and unsurprisingly, the effect of noise was greater in the evening, especially late evening during bedtimes. Regional differences, including culture, typical building construction systems, lifestyle, and weather, can influence noise annoyance as well. Also relevant, is the concept of *environmental load*. For a given noise level, inhabitants of small towns seem to be less annoyed than those living in large urban communities. It is also noted that with the same sound level, annoyance may differ, with different types of noise. General research shows that, aircraft noise is more annoying than road traffic noise; whereas road noise is more annoying than railway noise, although it has been suggested that this may not be true for all countries and cultures.

### *6.2.2 Noise Indicators*

In addition to basic sound indicators such as SPL and *loudness*, a number of supplementary noise indicators have been developed, some of which are described below.

The equivalent continuous sound level, $L_{eq}$, widely used to measure noise which varies considerably with time, is a notional sound level. It is 10 times the logarithm (to the base ten) of the ratio of the time-mean-square instantaneous sound pressure, during a stated time interval, to the square of the standard reference sound pressure.

$L_n$ is the level of noise exceeded for n% of the specified measurement period. In other words, if $N$ measured SPLs are obtained in a time period $T$ with a given time interval and they are sorted in a descending order, and then $L_n$ is the $(100n/N)$th SPL in the order. By convention, $L_1$, $L_{10}$, $L_{50}$, and $L_{90}$ are used to give approximate indications of the maximum, intrusive, median, and background sound levels, respectively.

Day-night average sound level (DNL), or day-night equivalent sound level, $L_{\mathrm{dn}}$, is the average of noise levels $L_p$ over a 24 h period, but the noise level during the night-time period, typically 22:00–07:00, is weighted by the addition of 10 dBA. Day-evening-night level, $L_{\mathrm{den}}$, is similar to DNL but an evening period is considered, weighted by the addition of 5 dBA. It is currently used widely in Europe (EU 2002).

### *6.2.3 Noise Standards and Regulations*

The main factors of environmental noise legislation include adverse public health effects, annoyance of residents within a neighborhood, and risk management strategies of the legislatures. There are two typical approaches when assessing environmental noise impact, the first is based on absolute sound levels, and the second looks at the increase of the existing ambient sound levels due to new or expanded development.

In 1992, the World Health Organization (WHO) Regional Office for Europe convened a task force meeting who created health-based guidelines for community noise (Berglund et al. 1999), aimed at establishing a methodology for deriving noise standards within a framework of noise management. Table 6.1 shows the guideline values for selected environments.

The prominent international standard ISO 1996 (ISO 2003) concerns the description and measurement of environmental noise. It contains three parts, namely: (1) basic quantities and procedures; (2) acquisition of data pertinent to land use; and (3) application to noise limits. It is noted that although Part 3 of the standard lays down guidelines for the ways in which noise limits should be specified, and describes procedures to be used for checking compliance with such limits, no specific noise limits are actually stated. The standard assumes that noise limits are established by relevant government bodies.

The EU Directive of the European Parliament and of the Council relating to the assessment and management of environmental noise (EU 2002), which aims to establish a common EU framework.

In England, The Planning Policy Guidance Note 24 (PPG 24) (ODPM 1994) gives advice to local planning authorities on how the planning system can help to

**Table 6.1** WHO recommended guideline values for community noise in specific environments (adapted from Berglund et al. (1999)

| Specific environment | Critical health effect(s) | $L_{Aeq}$(dB) | Time-base ($h$) | $L_{A\max}$(dB) (fast) |
|---|---|---|---|---|
| Outdoor living area | Serious annoyance, daytime and evening | 55 | 16 | |
| | Moderate annoyance, daytime and evening | 50 | 16 | |
| Dwelling, indoors Inside bedrooms | Speech intelligibility and moderate annoyance, daytime and evening | 35 | 16 | 45 |
| | Sleep disturbance, night-time | 30 | 8 | |
| Outside bedrooms | Sleep disturbance, window open (outdoor values) | 45 | 8 | 60 |
| Hospitals, ward rooms, and indoors | Sleep disturbance, night-time | 30 | 8 | 40 |
| | Sleep disturbance, daytime and evening | 30 | 16 | |
| Industrial, commercial, shopping and traffic areas, indoors and outdoors | Hearing impairment | 70 | 24 | 110 |
| Ceremonies, festivals, and entertainment events | Hearing impairment (patrons: <5 times/year) | 100 | 4 | 110 |

**Table 6.2** Recommended limits in PPG24 for various noise exposure categories for new dwellings near the existing noise sources in $L_{\mathrm{Aeq},T}$ (*Source* ODPM 1994)

| Noise source | Time periods | Noise exposure category (NEC) | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Road traffic | 07.00–23.00 | <55 | 55–63 | 63–72 | >72 |
| | 23.00–07.00 | <45 | 45–57 | 57–66 | >66 |
| Rail traffic | 07.00–23.00 | <55 | 55–66 | 66–74 | >74 |
| | 23.00–07.00 | <45 | 45–59 | 59–66 | >66 |
| Air traffic | 07.00–23.00 | <57 | 57–66 | 66–72 | >72 |
| | 23.00–07.00 | <48 | 48–57 | 57–66 | >66 |
| Mixed sources | 07.00–23.00 | <55 | 55–63 | 63–72 | >72 |
| | 23.00–07.00 | <45 | 45–57 | 57–66 | >66 |

minimize the impact of noise. It introduces the concept of noise exposure categories (NECs) for residential development. NECs range from *A*–*D*, with Category *A* representing circumstances in which noise is unlikely to cause annoyance, Category *D* relates to situations where development is normally refused, and Categories *B* and *C* deal with situations where noise mitigation measures could make development acceptable. Table 6.2 shows noise limits given in PPG 24 which correspond with NECs for new dwellings.

## 6.3 Modeling Urban Acoustic Environment

As most acoustic problems cannot be resolved purely through practical analysis, engineers heavily rely on computer simulation which is continuously developing. Essentially, models for calculating sound distribution in urban areas can be classified into two groups: *microscale* and *macroscale*. The former, as discussed below in Sect. 6.3.1, are often based on simulation techniques and used for accurately calculating the sound field for small and medium scale urban areas, such as a street or a square. The latter, as discussed below in Sect. 6.3.2, normally involve statistical methods and simplified algorithms, and generally adopted for analyzing sound distribution in relatively large urban areas.

Another relevant approach is physical scale modeling, which has been used for simulating environmental sound propagation for a number of years. A notable advantage, compared with computer simulation, is that some complex acoustic phenomena can be replicated more accurately, such as diffraction behavior of sound when it meets obstacles. Compared with real measurements in urban areas, a significant advantage of scale modeling is that the geometry, source, and receiver condition, as well as background noise are relatively easy to control.

### *6.3.1 Computer Models for Urban Sound Propagation at Microscale*

The *image source method* treats a flat surface as a mirror and creates an image source. In other words, the boundaries are regarded as geometrically reflective. The reflected sound is then modeled with a sound path, directly from the image source, to a receiver. Multiple reflections are achieved by considering further images of the image source. For each reflection, the strength of the image source is reduced due to surface absorption (Kang 2000, 2002a). A disadvantage of the image source method is that the calculation speed is reduced exponentially with increasing orders of reflection as the number of images increases. In addition, validity and visibility tests are required for image sources.

*Ray-tracing method* is another commonly used simulation method. It creates a dense spread of rays, which are subsequently reflected around a space and tested for intersection with a detector (receiver) such as a sphere or a cube. A sound ray can be regarded as a small portion of a spherical wave with vanishing aperture, which originates from a certain point. Particle-tracing method uses similar algorithms to ray tracing, but the method of detection is different. With the particle model, the longer a particle stays in the detector, the higher its contribution to the energy density is. Beams are rays with a nonvanishing cross-section. The beams may be cones with a circular cross-section or pyramids with a polygonal cross-section. By using beams, a point detector can be used, instead of a sphere or a cube. Beams are reflected around a space and tested for illumination of the detector. An advantage of ray-, particle-, and beam- tracing methods, is that they can be used for relatively complicated urban configurations, but they are usually used for acoustically smooth boundaries, namely geometrically reflective boundaries. Since there are always some irregularities on building or ground surfaces, it is necessary to consider diffuse reflections from boundaries, namely diffusely reflecting boundaries.

The *radiosity method* provides an effective way for considering diffusely reflecting boundaries. The method functions by dividing boundaries, in a space such as an urban street or square, into a number of patches (i.e., elements) and replaces the patches and receivers with nodes in a network. The sound propagation within the space can then be simulated by energy exchange between those nodes. Various computer programs have been developed based on radiosity method, which are applicable to urban spaces such as street canyons and urban squares (Kang 2001, 2002b, 2005). A model combing ray tracing and radiosity has also been developed and well-validated against measurements (Kang 2006).

With the development of more powerful computers, a number of other models, based on numerically solving wave equations, have also been developed and applied in urban situations, including: acoustic *finite element method* (FEM) and *boundary element method* (BEM) (Hothersall et al. 1996), *equivalent sources method* (ESM) (Ögren and Kropp 2004), *finite difference–time domain* method (FDTD), and *parabolic equation* method (PE) (Van Renterghem et al. 2005).

### 6.3.2 Macroscale Urban Sound Propagation and Noise Mapping

A noise map is a way of presenting geographical distribution of noise exposure, either in terms of measured or calculated levels. Although microscale simulation techniques, as described above, can generate relatively accurate predictions of urban sound propagation, it is generally inappropriate when applying these algorithms at a macroscale (e.g., whole city). A number of software packages have been developed for large area noise mapping, based on a series of simplified algorithms, specified in various standards, internationally (ISO 1993) and nationally, for various noise sources including aircraft, road, railway, and industry. Figure 6.1 shows two examples of noise maps (Wang and Kang 2011).

In ISO 9613, the equivalent continuous downwind octave band SPL at a receiver position is determined by considering the sound power level of the source, a directivity correction, and the attenuation between source and receiver, which includes the geometrical divergence, atmospheric absorption, ground effects, barrier effects, and miscellaneous effects.

Much effort has been made to develop source models for road traffic (Watts 2005). Noise source points on vehicles are simplified by adopting just two point sources: first, a low source height at 0.01 m above the road surface, which typically represents tyre/road noise; and second, a higher source point, which largely reflects propulsion noise (e.g., engine) with height dependent on the vehicle category.

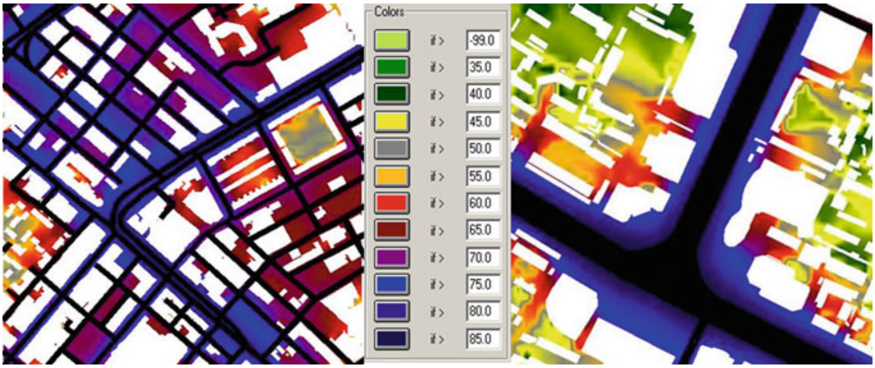


**Fig. 6.1** City noise maps (**a**) Greater Manchester, UK (**b**) Wuhan, China (*Source* Wang and Kang 2011)

For geometrical divergence in a free field, at a distance $d$ from a point source the intensity is the sound power of the source $W$ divided by the total spherical area of the sound wave at $d$

$$I = \frac{W}{4\pi d^2} \tag{6.1}$$

In other words, the intensity at any point is inversely proportional to the square of its distance from the source, which is commonly referred as inverse-square law. This is equivalent to a reduction of 6 dB SPL at each doubling of the distance from the source. The SPL can be calculated in reference to the sound power level, by

$$L_p = L_W - 10\log(4\pi d^2) = L_W - 20\log(d) - 11 \tag{6.2}$$

For hemispherical sound propagation where the source is located close to a hard ground and reflections of the emitted noise occur, the above equation becomes

$$L_p = L_W - 20\log(d) - 8 \tag{6.3}$$

In terms of atmospheric absorption, temperature and relative humidity are important. Generally, the effect is only significant at large distance and/or at high frequencies (ANSI 1999).

## 6.4 Urban Noise Mitigation

While urban noise mitigation includes many aspects, this section mainly discusses the mitigation measures relating to the urban and building design, including building planning and design (Sect. 6.4.1), vegetation (Sect. 6.4.2), and noise barriers (Sect. 6.4.3).

### 6.4.1 Building Planning and Design

In many instances, it would be ideal to distance a building from external noise sources. According to an inverse-square law, separation is only effective when the source and receiver are originally positioned in close proximity. For example, moving from 10 to 20 m apart and from 100 and 200 m apart, each gives a 6 dB reduction for point source and 3 dB for line source.

While large and solid building façades can effectively reflect acoustic energy, it is possible to orient buildings, so that sound reflection can be directed to less sensitive areas, reducing annoyance. Alternatively, reflective façades can be made absorbent or to diffuse sound effectively. Care should be taken with curved façades, because they can focus acoustic energy into a small region of a receiving area, and thus significantly increase localized noise level.

Building form can reduce the internal impact of external noise to some degree. Figure 6.2 illustrates some examples and principles. In Fig. 6.2a, a podium, usually for commercial use, acts as a noise barrier for the main building which is typically residential. In Fig. 6.2b, the higher floors, typically bedrooms, are farther from the noise source and they are also 'protected' by the lower levels due to a screening effect. In Fig. 6.2c, balconies can effectively stop direct sound from source to windows/doors. Lastly, in Fig. 6.2d, a courtyard wall acts as a noise barrier (Kang 2006).

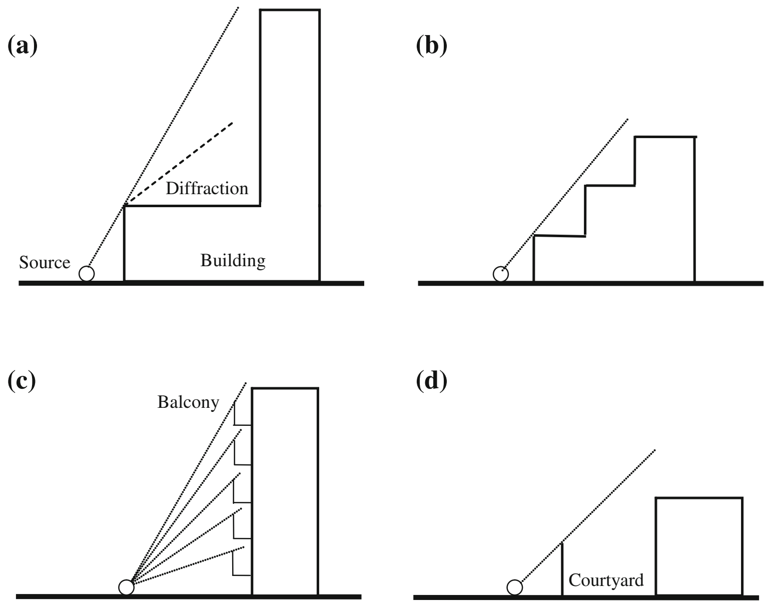


**Fig. 6.2** Principles and examples of self-protection buildings, cross-section view (*Source* Kang 2006)

Windows of buildings in noisy environments often need to be sealed, discouraging low energy strategies based on natural ventilation. A window system has been developed to overcome this problem (Kang and Brocklesby 2004; Kang and Li 2007). The core idea is to create a ventilation path by staggering two layers of glass and using transparent *microperforated absorbers* (MPA) (Kang and Fuchs 1999) along the path created to reduce noise. The system considers ventilation performance by focusing on the need to achieve occupant comfort through air movement, rather than only the requirement for minimum air exchange.

### 6.4.2 Vegetation

Mature evergreen vegetation that is several meters wide, can provide modest attenuation of several dB if the canopy is sufficiently high and long, has dense foliage extending to the ground, and can be well maintained. Wide belts of tall dense trees of a depth of 15–40 m appear to offer an extra noise attenuation of 6–8 dB at low (around 250 Hz) and high frequencies (>1 kHz) (Kotzen and English 1999). Nevertheless, tree and shrub arrangement is important. A linear tree planting arrangement has been shown to offer useful 'sonic crystal' effects including 'stop-bands', giving rise to more than a 15 dB reduction in transmitted sound in a particular frequency range, as long as the filling ratio is sufficiently high (Umnova et al. 2006).

Vegetation can be more effective in urban areas, such as a street canyon or a square, where acoustic problems behold multiple reflections that increase sound levels. In an urban context, the acoustic effect of vegetation has three key characteristics: sound absorption; sound diffusion which both occur when sound waves impinge on vegetation and then reflected back; and thirdly, sound level reduction, when sound waves are transmitted through vegetation. It has been shown that increasing boundary absorption can achieve a substantial reduction in SPL, and compared with geometrically reflecting boundaries, with diffusely reflecting boundaries there is also a significant SPL reduction. Consequently, when vegetation features on building façades and the ground, the effectiveness of absorption can be greatly enhanced, since there are multiple reflections. Similarly, due to multiple reflections, the diffusion effect of vegetation is significant, even when the diffusion coefficient is relatively low. While the transmission effect in an open field might not be significant, unless the density and depth are considerable, it could be, if multiple reflections are considered.

### 6.4.3 Noise Barriers

A barrier can be considered as solid obstacles which impede the line of sight between source and receiver, and thus creates a *sound shadow*. The effectiveness of a barrier is primarily dependent on the frequency and path difference, $\delta$, defined as the difference in distance between the direct path through a barrier from source to receiver and the indirect path over the barrier, as shown in Fig. 6.3, $R$ is the distance between source and barrier (m), $D$ is the distance between barrier and receiver (m), and $H$ is the effective height of barrier (m), namely the barrier height above the line between source to receiver. If the source-receiver line is perpendicular to the barrier, $\delta$ can be calculated by:

$$\delta = R[\sqrt{1 + (\frac{H}{R})^2} - 1] + D[\sqrt{1 + (\frac{H}{D})^2} - 1] \tag{6.4}$$

The extra attenuation of a barrier is closely related to the Fresnel number, $N$, defined as below, relating to wavelength $\lambda$

$$N = 2\frac{\delta}{\lambda} \tag{6.5}$$

For a single point source, Kurze and Anderson (1971) gave a simplified equation to calculate the performance of an infinitely long barrier. For $N > 12.5$, experimental data show that there is an upper limit of 24 dB. For $-0.2 < N < 12.5$, the insertion loss (IL), namely the SPL difference between with and without the barrier, can be calculated by

$$IL = 20\log\frac{(2\pi N)^{\frac{1}{2}}}{\tanh(2\pi N)^{\frac{1}{2}}} + 5 \tag{6.6}$$

In the above equation, ground effect is not considered. Unless the receiver is much higher than the ground, say over 2 m, the effect of ground reflection should be calculated by applying the above method for the image of the source/receiver, as shown in Fig. 6.3 (if the ground is perfectly reflective).

Environmental noise barriers can be made with a range of materials including timber, sheet metal, concrete, brick, plastic, PVC, and fibreglass. Transparent barriers are also rather common, using laminated, toughened or reinforced glass, acrylic, or polycarbonate sheet. In some cases, barriers are combined with solar panels.

Considerable research has been carried out to refine the design of areas at the top of barriers to maximize attenuation through diffraction. The beneficial effects

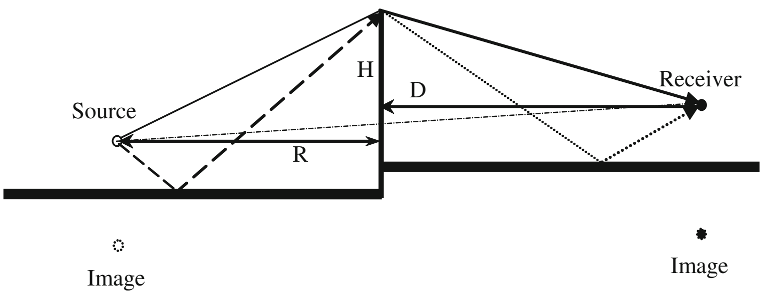


**Fig. 6.3** Diagram of calculating diffraction over a barrier

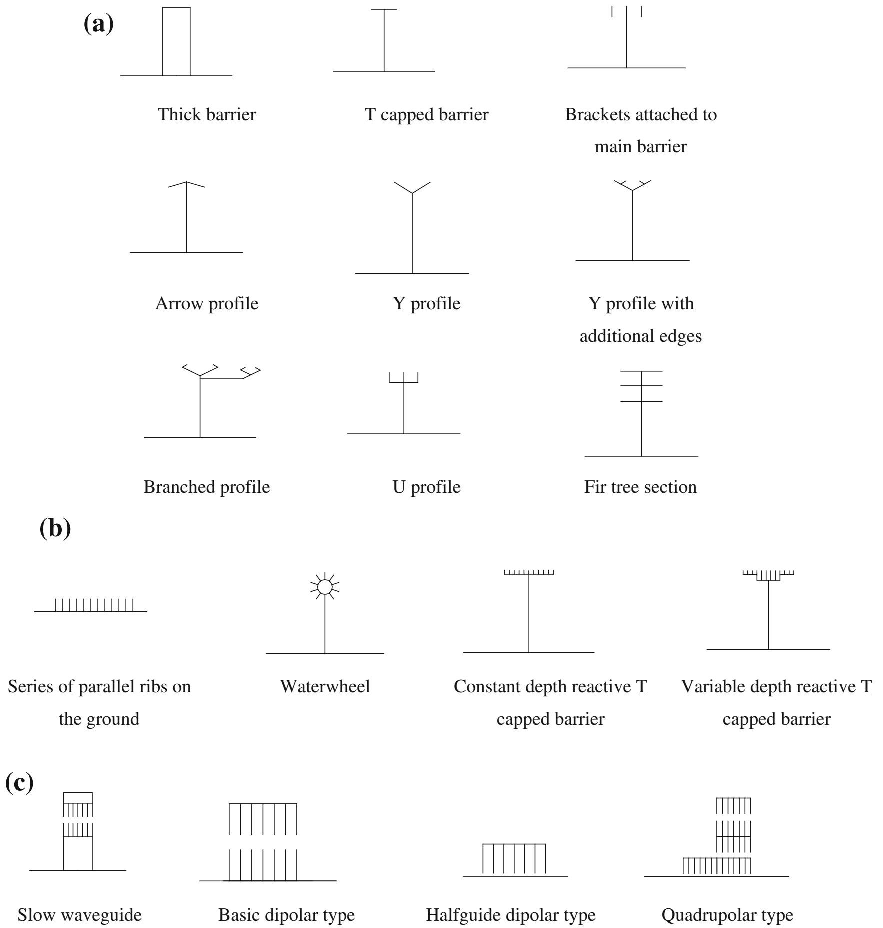


**Fig. 6.4** Schematics of strategic barrier designs, cross-sectional view. (**a**) Multiple-edged barriers (**b**) Reactive barriers (**c**) Phase reversal barriers. Adapted from Ekici and Bougdah (2004)

of additional diffracting edges have been demonstrated with fir tree profiles, T-shaped profiles, Y-shaped profiles, arrow profiles, branched barriers, and U-sections which involve constructing extra panels, connected to the main screen, using brackets. Some examples are illustrated in Fig. 6.4a. It has been shown that the insertion loss caused by extra diffracting edges could be about 3–5 dBA. The noise shielding efficiency of different shapes of absorbing obstacles on top of a barrier edge is generally up to 3 dB (Ekici and Bougdah 2004).

Reactive noise barriers have been explored, with some examples shown in Fig. 6.4b. An experimental study by Bougdah et al. (2006) demonstrated that with strategic designs, rib-like structures on the ground can be very effective in providing insertion loss, typically 10–15 dB over a rather wide frequency range. For wave guide and phase reversal barriers, as shown in Fig. 6.4c, noise reduction is achieved by the destructive interference of the waves going through the openings, with the waves diffracted over the top. Picket barriers and vertically louvered barriers are also based on similar principles.

## 6.5 Urban Soundscape

While reducing noise level remains the focus in acoustic regulations and noise policies across the world, it is widely accepted that reducing sound level is not always feasible or cost-effective, and more importantly, will not necessarily lead to improved quality of life and general satisfaction. For example, recent studies in urban open spaces showed that changes of sound level below a certain value (as high as 65–70 dBA) result in little or no impact on people's acoustic comfort. Conversely, where nonacoustic factors such as type of sound source and people's psychological characteristics are present, acoustic comfort can vary considerably.

Soundscape research, different from noise control engineering, is about relationships between the ear, human beings, sound environments, and society. Research in soundscape covers physical science, engineering, social science, humanity, medicine, and art. The field has evolved from within the academic disciplines of anthropology, architecture, ecology, design, human geography, linguistics, medicine, noise control engineering, psychology, sociology, and more recently computer simulation and artificial intelligence. As a global concept, it may also be fruitful to integrate insights from knowledge or values produced by every culture, therefore involving the literature and musicology, and more generally art, esthetics, laws, and religious studies as well. Soundscape research represents a timely paradigm shift in that it considers environmental sounds as a "resource" rather than a "waste". It is powerful than the classic level-based approach which is only suitable for providing primary needs such as sleep and hearing protection. It becomes even more prominent when a society reaches the highest needs: respect for others and creativity and spontaneity. Soundscape focuses more on the local individual needs and has esteem for the noise sensitive and other vulnerable groups. This section briefly discusses soundscape evaluation (Sect. 6.5.1), prediction (Sect. 6.5.2), and creation (Sect. 6.5.3).

### *6.5.1 Soundscape Evaluation*

An important part of the soundscape evaluation is to consider individual sounds (Schafer 1977). A list of sounds in various surroundings was evaluated, based on a survey in Japan (Tamura 1998). At the top of the list were the twittering of birds, rippling of water, insects/frogs, waves, and wind chimes, where 45–75 % of the subjects found these sounds favorable and 25–65 % found neither favorable nor annoying. The bottom five sounds were motorbikes, idling engines, construction work, campaigning vehicles, and karaoke restaurants; where 35–55 % of the subjects found these sounds annoying and 45–65 % found neither favorable nor annoying. In addition to the type of sound, the loudness may also influence the categorization/classification, especially at relatively high loudness levels. Moreover, the meaning of a sound may considerably influence the evaluation. Furthermore, not only perceptual factors, but also cognitive factors such as memory, play an important role in global loudness judgments.

*Social* and *demographic* factors play an important role in soundscape evaluation and considerable work has been devoted to this (Kang 2006). The assessment of sound quality in urban areas depends on how long people have been living there, how they define the area, and how deep they are involved in social aspect within the area. *Expectation* is another issue in soundscape evaluation. Similarly, noise regulations are often based on inherent assumptions which people expect from different noise environments depending on situational factors. Cultural differences may also lead to rather different acoustic comfort evaluation and sound preference. *Behavioral* factors should be considered too. For example, people with music amplification systems (stereos) may have different sound evaluation from others. It is also important to consider an individual's sound sensitivity, and equally people's attitude can be affected by sound. For example, it appears that loud noise reduces helping behavior and induces a lack of sensitivity to others (Page 1997).

The acoustic effects of an urban environment should be evaluated. Reverberation is an important index for the acoustic environment of urban streets and squares. With a constant SPL, noise annoyance is greater with longer reverberation. On the other hand, a suitable RT, say 1–2 s, can make street-music more enjoyable. Depending on the usage of an urban open space, an appropriate reverberation might be determined, although the requirements are much less critical than those in auditoria.

The interaction between acoustic and other physical conditions is an important aspect of the soundscape evaluation in urban environment. For example, if a place is very hot or very cold, the acoustic comfort can become less critical in the overall comfort evaluation. Of various physical conditions, the aural-visual interactions have been intensively studied. A study with controlled aural and visual stimuli suggested that the more urban in nature, visual settings were the more contaminated the auditory judgment was (Viollon et al. 2002).

### *6.5.2 Soundscape Prediction*

For urban planners and architects, it would be useful to develop a tool to predict the subjective evaluation of soundscape quality by potential users, using known design conditions such as physical features of a space, acoustic variables, and people's characteristics.

A bottom-up approach has been used by De Coensel and Botteldooren (2007), where the individual sensory, cognitive, and emotional mechanisms which play a role in soundscape perception are discerned, and a human mimicking software

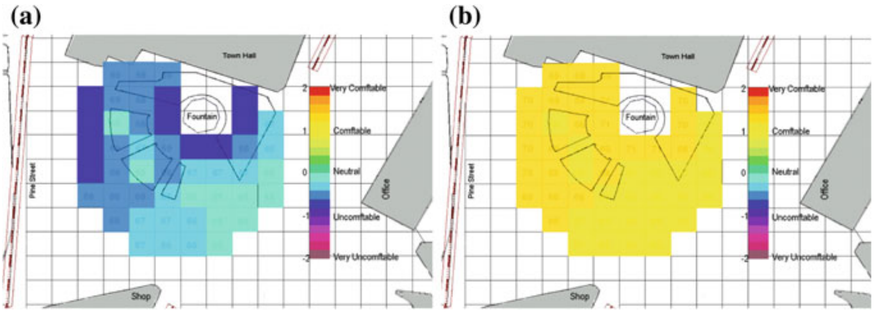


**Fig. 6.5** Acoustic comfort map of the *Peace Gardens*, Sheffield. (**a**) People from noisier homes (**b**) People from quieter homes

model was proposed. Since human listeners process sound as meaningful events, Niessen et al. (2009) developed a model to identify components in a soundscape which are the basis of these meaningful events.

Another approach is the use of artificial neural networks (ANN) technique, with which models have been developed to predict soundscape perception, including sound level and acoustic comfort evaluation, with input including social, demographical, psychological, cultural, behavioral factors, and sound distribution (Yu and Kang 2009). Figure 6.5 is an example of an acoustic comfort evaluation map, showing that people from nosier homes will feel less comfortable acoustically in an urban open space.

To aid urban soundscape design, as well as for public participation, it is useful to present the 3D visual environment with an acoustic animation/auralization tool, where consideration is given to various urban sound sources, dynamic characteristics of the sources, and movements of sources and receivers. The calculation speed should be reasonably fast, so that a designer can adjust the design, listen to the difference and create an instant evaluation (Smyrnova and Kang 2010).

### *6.5.3 Soundscape Creation*

In urban open public spaces, it has been shown that if the overall sound level is higher than a certain value, say 65–70 dBA, and people will feel annoyed, regardless of sound type. It is important to reduce sound levels in these specific situations. Conversely, if the overall sound level is not high, sound source type is more important (Yang and Kang 2005a, b). A model for describing the soundscape of urban open spaces is shown in Fig. 6.6.

When designing a soundscape in an urban open space, it is useful to consider soundmarks, reflecting traditional and cultural characteristics. Sound sources in an urban open space can be divided into two types, namely *active* sounds and *passive* sounds. Active sounds relate to noise from the activities in the space; and passive

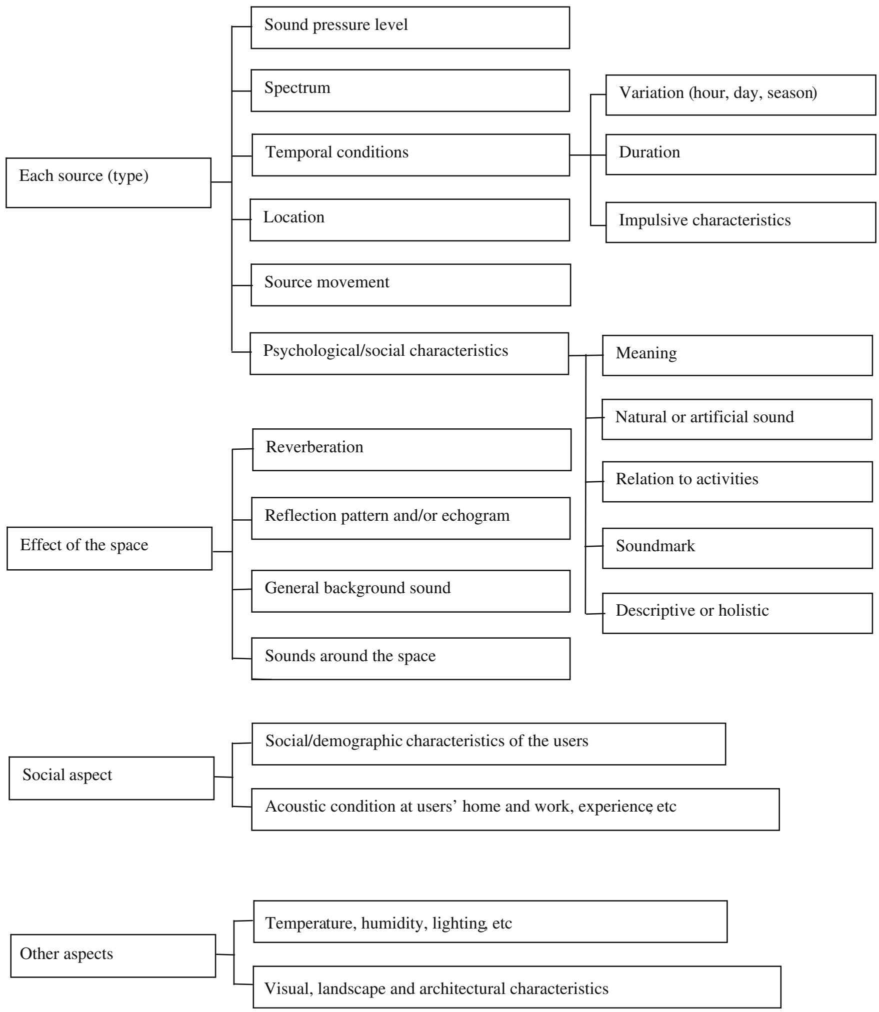


**Fig. 6.6** A model for describing the soundscape of urban open spaces

sounds relate to noise originating from landscape elements. As a typical active sound, live music is always very popular. People are not only interested in the music itself, but are also attracted by the activities of the players. In this case, the type of music (e.g., classical music or pop music) is not a very important issue. However, when music is played using loudspeakers, the type of music as well as the sound level can significantly determine popularity. As a typical passive sound, water is attractive to most people, but particular attention must be paid to the water flow rate, which should not be constant. Keeping it at the same sound level range encourages people's disinterest, so that psychological effects diminish over time.

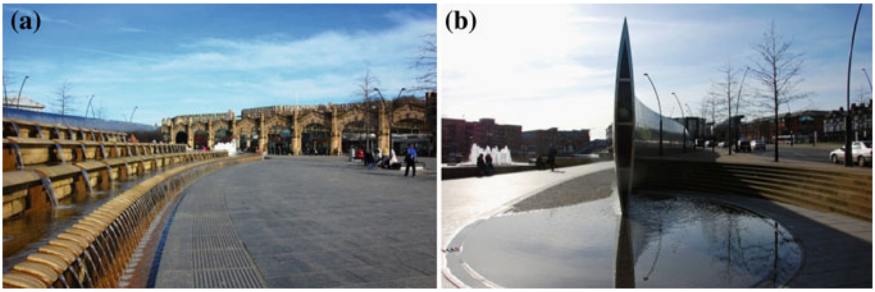


**Fig. 6.7** The Sheaf Square. Sheffield, UK (**a**) Water features (**b**) Steel barrier

Both active and passive sounds can be used to mask the undesirable noises. In this case, although the overall sound level may not decrease (it may even increase), people feel that the acoustic environment is more comfortable. Spectrum analysis is important, both for individual sounds and for the overall acoustic environment. For example, a survey on different water features suggests that high frequency components generally originate from splashing water, whereas low frequencies are created from large water flows that fall from considerable heights onto a hard surface.

The creation/design of soundscape in an urban open space should be considered as a dynamic process. Soundscape variation due to seasonality, month, and different times of typical days, should be taken into account, as well as differences in soundscape between the designed space and the surrounding acoustic environment.

Effects of architectural changes and urban design options on sound fields of urban open spaces have been studied using computer models (Kang 2002a, 2006), showing that soundscape can be effectively changed by architectural and urban design.

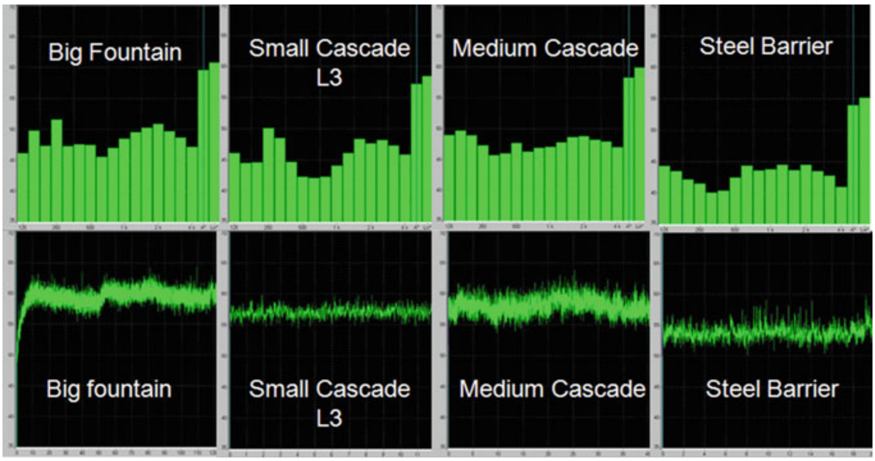


**Fig. 6.8** Changes of sound levels with frequency and time at different locations of the Sheaf Square, measured at 1 m from each water feature

The *Sheaf Square* in Sheffield, UK, as shown in Fig. 6.7, provides interesting and enjoyable soundscapes. There are a number of water features and measurements show that they vary considerably in terms of spectrum and dynamic process, as demonstrated in Fig. 6.8. The steel barrier, shown in Fig. 6.7b, is a very successful soundscape element, which efficiently reduces noise from the busy road and also generates pleasant water sounds.

This case demonstrates potentials in analyzing soundscapes, which enable and empower professionals to manage sound effectively in permissible circumstances.

## 6.6 Conclusions

Throughout the various physical layers of urban society, acoustics, or urban *soundscapes*, can impact on people's physiological and psychological wellbeing. Undesirable noise can seriously degrade the experience of occupants living in problem locations; or conversely, a well-designed urban environment that has considered acoustic impact, can bolster work productivity and general wellbeing through understanding physical properties of form. Over the years, robust methodologies have been developed to cope with measuring, assessing, modeling, and manipulating sound to our advantage. It is also well-known, the determining factors that contribute to our perception of sound and how they impact on how we relate to our immediate environment. International standards and regulations exist to control and manage the acoustic environment; these have been created by robust methodologies, facilitated by the use of models in which to simulate soundscapes. This, together with experimental work, has enabled us to integrate acoustic design into our built environment; and to exploit the benefits of sound and the way it can be advantageously introduced into everyday life. Understanding of the science that underpins acoustic engineering can lead to some subtle interventions that propagate profound positive impacts on our perception of the built environment.

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# Chapter 7
# Sustainable Urban Drainable Systems for Management of Surface Water

**Chuck Yu**

**Abstract** Sustainable Urban Drainage Systems (SUDS) provide a system by which water drainage can be managed as closely as possible to what nature has intended, before the runoffs from urban development enter the watercourses. The system removes water quickly and efficiently in a sustainable manner and should be included in the masterplanning for building and urban development wherever possible. The SUDS concept is an integrated approach to surface water management, which equally considers quality, quantity, and amenity aspects to provide a more pleasant habitat for people as well as to increase the biodiversity value of the local environment. The growing demand for housing and commercial developments in the twenty-first century, as well as the environmental pressure caused by climate change, has increased the focus on sustainable construction and SUDS. The management of water quality is required by the European Union Water Framework Directive. Stakeholders should be consulted in every development for masterplanning to include SUDS to minimize impact on the local environment and land use; and also to mitigate risk of flooding and pollution on watercourses. There should be adequate care of the environment, as well as social and economic considerations in building development. *Learning outcomes*: On successful completion of this chapter, students will be able to: (1) Understand the requirements for sustainable surface water drainage for a building development. (2) Grasp the concept of sustainable urban drainage systems and the treatment train (sequence). (3) Have knowledge of SUDS techniques and their applicability. (4) Scope study, survey of ground soil, and hydrology characteristics of the site. (5) Appreciate land use and planning consent. (6) Gain insight into SUDS management.

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**Keywords** Green roofs · Infiltration · Master planning · Pervious paving · Soakaway · Source control · Stormwater · SUDS · Surface water management · Swales

## 7.1 Introduction

*Diffuse pollution* is closely related to land use; and the majority of urban diffuse pollution is caused by runoff from areas with impermeable surfaces, such as industrial and commercial estates, construction sites, roads, and other urban areas. Development of land reduces the surface permeability of rainwater by replacing green field areas with impermeable structures. Such development leads to an increase in surface water runoff, and consequently reduces the amount of water infiltrating into the ground.

The runoffs may contain substances that can deteriorate the water quality of nearby water catchments when the wastewater flows into drains and into watercourses, thus affecting the ecology of water catchment habitats, drinking water resources, and amenities. Misconnections of foul water to surface water, either by flooding or poor plumbing work, could also exacerbate surface water quality. Flooding also removes large quantities of surface water over a short period of time, leading to erosion of riverbeds, damaging watercourses, and habitats.

Sustainable Urban Drainage Systems (SUDS) provides a system by which water drainage can be managed as closely as possible to what nature has intended, before it enters the watercourses; the system removes water quickly and efficiently in a sustainable manner and should be included in the master planning for any building and urban development wherever possible. SUDS should be considered as a design and planning issue, such as quantity of water removal, pollution control, creation, and enhancement of habitats and biodiversity preservation. SUDS principal source control strategy includes the use of *grasscrete* for car park surfaces, permeable asphalt, paving, grass swales and vegetated bio-filters, ponds, and wetlands. SUDS are increasingly required by many local authorities to mitigate flood risk due to excessive surface water runoffs in urban areas and may include infiltration devices to reduce pollution contained in the runoffs. It is essential that surface water runoff from buildings is removed as quickly and as safely as possible without causing damage to them; in doing so, stormwater runoff poses no risk to people or the environment through flooding or pollution.

## 7.2 SUDS Concept

Land drainage is required to render it suitable for development, to protect existing and proposed development from the effects of flooding, and to manage pollution that could arise from the interaction of rainwater and development runoffs. Figure 7.1 provides a simple representation of the SUDS concept.

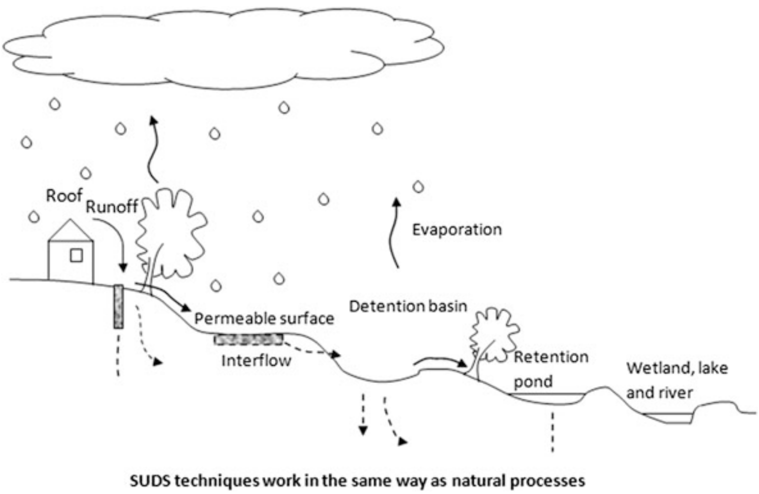


**Fig. 7.1** The SUDS concept and hydrology cycle (*Source* Bregulla et al. 2010)

Sustainable drainage is a concept that includes long-term environmental and social factors in decision making about drainage. It takes account of the quantity and quality of runoff, and the amenity value of surface water in the urban environment (Bregulla et al. 2010). SUDS provide an integrated approach to surface water design problems which consider quality, quantity, and amenity aspects equally to provide a more pleasant habitat for both amenity of people as well as increasing the biodiversity value for the area (Bregulla et al. 2010; CIRIA 2007; Environment Agency 2011). Growing demand for housing and commercial developments across the world, as well as the increasing environmental pressure surrounding climate change, has heightened the focus on sustainable construction and SUDS.

SUDS are more sustainable than conventional drainage systems because they are: designed to manage flow rates; protect and enhance water quality; sympathetic to environments and the needs of the local community by controlling rainwater at source; attenuating flows and regulating discharge to green field runoff. The conventional piped drainage system in developed areas is now unsustainable in the present climate and in areas where frequent surface stormwater is expected. In dry periods when flows are low, these systems can often silt up, causing a problem by reducing the capacity to deal with heavy flow of stormwater, contributing to flooding and pollution of watercourses. Also, by collecting rainfall in piped systems, the amount of water infiltrating the ground will be significantly reduced, depleting groundwater and reducing flows in watercourses during dry weather spells. As a result, many urban watercourses have become lifeless and are often hidden underground in culverts, and in many cases, built upon in certain urban areas.

Traditional surface water drainage uses underground piping systems to convey runoff from built-up areas as quickly as possible, without considering the effects downstream. Conventionally, surface water would be combined with wastewater (sewage) and drained through combined sewers. When during a rainstorm surcharge, the excessive water flow can overwhelm the conventional system, causing a burden on wastewater treatment work. Separate piping systems conveying surface water to watercourses and wastewater to sewers, can deal with large quantities of water runoff, but fail to provide adequate means of managing flood risk. However, they cannot control the poor quality of surface runoffs to minimize the impact on the water environment. In general, these systems were not designed with sustainable development in mind and would not contribute to the management of water resources, amenity, landscaping potential, or enhance biodiversity.

The SUDS concept (Bregulla et al. 2010; CIRIA 2007) consists of a 'Treatment Train' as follows:

- Provision of a management plan for the site developers/managers to ensure adequate upkeep of sites; this should include operation and pollution prevention manuals and to schedule programs to reduce sources of pollution at local levels;
- The design and management plan should include a reduction of impermeable surfaces including road and paving, and to encourage rainwater harvesting;
- Management depends on the purpose of the development, for an industrial site or vehicles station such as a garage, depot, or car park, there is a need to consider a containment strategy for storage and disposal of oil, fuel, and chemicals. For general households, gardens, or public roads, there is a need to consider the use of herbicides and pesticides and discharges of detergent and soap water wastes;
- The surface water management should have a thorough *Source Control* strategy to control runoffs from grounds and roof surfaces of a building (see Sect. 3.1 below);
- Attenuation strategies are required for *Site Control* of housing estates, commercial shopping centers, or business parks;
- There should also be *Regional Control* to attenuate runoff flows within a region containing several development sites, a town, or a built-up area for instance.

Many developments will not need to follow the whole suite of SUDS techniques. The application of SUDS is mainly dependent on the required flow attenuation and is commonly managed through site control with a localized pond and surface water treatment to minimize the pollution risk in the local area. Skilful management characterized by pollution prevention and good maintenance practice, will always be required.

*Residential* sites are the least likely to cause severe pollution and developers can in many cases avoid unnecessarily elaborate solution for a small site, which would only require the first level of treatment using the SUDS techniques.

*Non-residential* sites such as shopping centers with car parks and larger housing estates incorporating access roads and bus stops would require first and second levels of treatment.

*Industrial* sites typically where manufacturing processes could potentially discharge chemical spillage, some of which can contain heavy metal toxins. This category also applies to trunk roads and sites for transport garages. Containment of pollutants is essential for such locations.

## 7.3 SUDS Techniques

This section looks at source control and the range of SUDS systems that can be employed to manage urban drainage.

### *7.3.1 Source Control*

Source control (Bregulla et al. 2010; CIRIA 2007) should form part of surface water management. It manages water through the use of prevention measures, which can make a significant contribution to minimize surface water runoff. These include:

- Minimizing paving areas to allow surface water runoff to drain naturally, through surfaces such as gardens and public green spaces;
- Use of porous surfaces where possible;
- Rainwater recycling by collecting rain water from roofs to be used for flushing toilets, landscape gardening, and washing cars;
- Minimizing pollution through good practices, training, and information. Informing site managers of how sites are drained and maintained and to keep paved areas clean, free of contamination from waste and litter.

Surface water management (CLG 2008) can be intensified by site control techniques to minimize the quantity of water discharged directly to a river. This includes:

- *Infiltration devices* to enhance the natural capacity of the ground to store and drain water at a local control level. These consist of vegetated land, grass verges, and grass swales which mimic natural drainage systems, controlling discharge to regional ponds, wetlands, or other discharge systems. These approaches allow removal of solid particles and pollutants before discharging into water effluent;
- *Soakaways* that create underground reservoirs which allow surface water to infiltrate gradually into subsoil;
- *Trenches* (usually alongside roads) to discharge water toward another structure or SUDS device at a controlled rate;
- *Filter drains*, *swales* and *infiltration devices* should be included to facilitate water treatment before it can be returned to the water cycle. These systems can contribute to control the flow and quality of runoff where surface water cannot be stored on-site;

- *Basins*, *ponds*, and *wetlands* are usually for regional control; to store surface water runoff infiltrated through soil. These can function to control temporary flooding, allowing settlement of solids and pollutants, or as a permanent water feature for the site.

## *7.3.2 SUDS Devices*

### 7.3.2.1 Green Roofs

'Green roofs' are also known as *roof gardens*, *vegetated roofs*, *living roofs* or *eco-roofs*. Such roofs are intentionally planted with vegetation forming part of the integral design. This can be anything from a rooftop garden with planted flowers, shrubs, grassy swards to patches of mosses, and lichens. A green roof can consist of a multilayer system which includes: a vegetation top layer, soil or a suitable substrate, drainage, protection, waterproofing, and insulation layers. There are two types of green roofs, although some buildings have a combination of both in the roofing system:

- *Extensive*—this covers the entire roof area with low growing, low maintenance plants. Extensive green roofs typically comprise a 25–125 mm thick soil layer supporting a variety of drought-tolerant, low, and hardy plants. Examples of extensive green roofs can be found online using the search term 'living roofs';
- *Intensive*—this includes a landscaped garden which has deep enough soil to support trees, plantains, and shrubs. Occasionally, water features and storage of rainwater or water harvesting system can be included. Intensive roofs can place substantial loads on roofing structures and require on-going maintenance of plants and water system itself.

There is a wide variety of green roofs that perform successfully across the world in different climates. The general criteria for green roofs types are shown in Table 7.1 (International Green Roof Association).

Green roofs can be incorporated into most roofing designs including pitched roofs, but are commonly integrated on flat roofs or slightly sloping roofs on commercial buildings, schools, sports centers, hotels, holiday homes, and apartment buildings. An example of a green roof on a commercial building (hypermarket) close to a housing development is given in Fig. 7.2. Green roofs can be easily retrofitted provided there is sufficient structural support within an existing building. The vegetation layer provides a degree of protection for the roof and reduces the effects of aging due to temperature stresses during summer and winter, the degradation caused by ultraviolet radiation of sunlight, and the varying ozone intensity of urban environments. The waterproofing layer is also protected from direct physical stresses caused by hail, rain, and wind as well as wear and tear caused by pedestrian traffic on roofs.

**Table 7.1** General criteria requirement for different types of green roofs

| | Extensive green roof | Semi-intensive green roof | Intensive green roof |
|---|---|---|---|
| Maintenance | Low | Periodically | High |
| Irrigation | No | Periodically | Regularly |
| Plant | Moss-sedum-herbs and grasses | Grass-herbs and shrubs | Lawn or perennials, shrubs, and trees |
| System build-up height | 0.06–0.2 m | 0.12–0.250 m | 0.15–0.4 m<br>Underground garages >1 m |
| Weight | 60–150 kg/m$^2$ | 120–200 kg/m$^2$ | 180–500 kg/m$^2$ |
| Costs | Low | Middle | High |
| Use | Ecological protection layer | Designed green roof | Park like garden |

*Source* International Green Roof Association

**Fig. 7.2** An intensive green roof on top of a hypermarket in Milton Keynes

Green roofs can moderate internal temperatures within buildings. It provides a heat shield for the roofing system and cools the building by transpiration which is a comfort advantage particularly during hot summers. In addition to providing good thermal insulation, green roofs can reduce noise reflection by up to 3 dB and improving sound insulation up to 8 dB. The vegetation can also provide an effective shield to electromagnetic transmission.

Green roofs can attenuate runoffs by intercepting and retaining rainwater during the early part of a storm, reducing the maximum runoff rate, resulting in reduced pressure on surface water drainage systems. Water is retained in the drainage and substrate layer which can be evaporated later over the surface. Water is also absorbed by the plants through photosynthesis and transpiration, releasing water vapor back into the atmosphere. Temperature, wind speed, substrate depth, and growing seasons are the major factors affecting water volume reduction from the total volume of water runoff that ultimately flows into drainage systems. Commonly used mineral substrate layers can achieve a water retention capacity between 18 and 50 %. Aggregates can also absorb and retain water. A retention capacity of 40–100 % of rainwater by various types of green roofs, depending on seasons, is also possible (Brenneisen 2001). One case study showed that a saturated infiltration capacity of 89 mm/h was attainable when using an extensive green roof, designed to retain a 24 h rainfall with an annual probability of 1 in 2 years (roof thickness cover was 70 mm and a 45 % moisture content in growth medium) (USEPA 2000). American research suggests that green roofs can attenuate storms with up to 50 % annual probability of exceedance within a 1 in 2-year return period. The volume of water that is stored on a green roof and evaporated back into the atmosphere is dependent on the vegetation medium, its depth, and the type of plants used. In summer, green roofs can typically retain 70–80 % of rainfall, whereas in winter they retain approximately 25–40 %.

The hydraulic design of green roofs should comply with BS EN 12056-3 (CLG 2000). The Code of practice for flat roofs with continuously supported coverings (BS 6229:2003) also provides useful information for roofing. German guidelines for the planning, execution, and upkeep of green roofs developed by the *Landscaping and Landscape Development Research Society* (FLL) in Germany (FLL 2002), have provided the industry with useful standards for construction of green roofs in Europe including the soil properties required for an extensive green roof and planting. Green roofs are included in the US green building assessment method Leadership in Energy and Environmental Design (LEED) (USGBC 2011). For further guidance on green roof construction, soil and plant selection, and planting see reference CIRIA 2007a.

#### 7.3.2.2 Pervious Paving

Pervious paving is a permeable hard-standing surface that allows passage of rainwater into the underlying construction, soil, or storage layer. They provide effective attenuation of water flow treatment. Pervious paving ameliorates the need for surface water drains, allowing runoffs to permeate through porous pavements, such as permeable concrete surfaces, crushed stones, or porous asphalts. Pollutants removal by filtration occurred within the surfacing or subbase material itself, or by the filtering action of the reservoir or subsoil. Some biological breakdown of organic pollutants can also occur.

Permeable surfaces can be designed to fit in with a variety of environmental settings, such as hard car park surfaces, town centers or gravel surfaces for light traffic. They can be grasscrete or soft landscape surfaces for rural areas. Infiltration devices can be incorporated into open space areas, such as playing field or car parks as a part of the flood management scheme.

Pervious surfaces are integral components for SUDS techniques, surface water management, and source control for the quantity and quality of runoff. The use of pervious paving is necessary for high density housing developments and a high percentage of hard surfacing for industrial and commercial developments. Surface water filters through the outermost layer and into the underlying construction layers where water is stored, prior to ground infiltration, reuse, or being released into watercourses or other surface water drainage systems. Pervious surfaces are often used for pedestrian paving, country paths, driveways, car parks, cycle-routes, and sports grounds. Pervious surfaces can be either porous or permeable, involving the following materials and techniques:

- Porous surfacing allows water to infiltrate across the entire surface of the material which forms the paving or car parking area for instance. Materials include grass and gravel surfaces, porous asphalt, and porous concrete;
- Permeable surfacing can also include proportions of impervious material; however, voids are present within these materials which allow water infiltration through gaps or cracks which act as void channels. Paving sand is commonly used to fill gaps in concrete paving slabs for example.

Impermeable membranes can also be used to line the sides and base of pavement beddings if water storage is required or if ground infiltration is unwanted (e.g., in water harvesting applications).

Pervious surfaces can be applied to a wide variety of developments, such as domestic housing, commercial and retail parks, industrial estates or car parks, and these provide filtration and attenuation of surface water including rainwater on the surface and also provide a drainage path for runoff from adjacent areas, such as from roofs or driveways. A pervious system used in a housing development is shown in Fig. 7.3.

Pervious surfaces provide surface water treatment through the following mechanisms:

- Filtration;
- Biodegradation of organic pollutants such as fuels from motor vehicles;
- Adsorption (this will depend on the materials of the pervious paving);
- Retention and settlement of solids;
- Impermeable bases provide a means of controlling direct flow to groundwater;
- The adsorption of subsoil within the pervious paving system is further enhanced by adding an adsorbent substrate material (e.g., sawdust, peat, clay, and granular activated carbon);
- Biodegradation of organic pollutants and other hydrocarbons.

The inclusion of a geomembrane in the construction of pervious paving can enhance the retention of oil. The incorporation of geotextile within the pervious paving system would also increase adsorption of heavy metals, nitrites, and ammonia. Comparatively, much lower concentrations of suspended solids, total solids, chromium, aluminum, copper, zinc, and lead can be expected in the drainage water of the pervious paving system compared with effluents collected

**Fig. 7.3** Previous paving in a housing development in Milton Keynes

from impermeable surfaces. Guidance is given in CIRIA C582 on the design criteria for source control (CIRIA 2002).

Pervious paving can be constructed in all soil types. If infiltration is required, groundwater must be at least 1 m below the base of the construction and must comply with government regulations. In the UK, the *Environment Agency* should be consulted in the early stages of development to agree with the nature and scope of any risk assessments. If the SUDS discharge is uncontaminated surface water, then discharge consent is not required. However, if the runoff into the SUDS possibly contains high concentrations of pollutants and the SUDS runoff will require treatment before discharge to watercourses, then discharge consent is required from the Environment Agency in the UK. In situations where discharge runs into a sewer, then discharge consent from the sewer operator is required. If infiltration is not required, the highest groundwater level should be below the base of the pavement structure.

Unlined pavements, those without membranes, should not be used in situations where water infiltration may cause slope instability or foundation problems which could result in landslides. Assessment by a chartered geotechnical engineer is required to provide advice on such situations and the effects of water storage on the structural integrity of the underlying soil must be ascertained. Unlined pavements should also not be used on contaminated land, unless sufficient evidence suggests that leaching of the contaminants is minimal.

The design surface water infiltration rate should be greater than the design rainfall intensity including allowance for runoff from adjacent impermeable areas. The infiltration rate must be much higher than the rainfall intensity so that the infiltration rate of the unmaintained paving area would still be sufficient to cope with the designed rainfall events. A reduction in the design infiltration rates of

90 % should be allowed for in the design to take account of the possibility of clogging by debris or silt. The storage volume of the surface water of the underlying layer should take 24–48 h to empty. For outflow via piped systems, the storage below the pavement should be designed as a tank system with limiting discharge rate. Where the surface slopes, the water storage would be wedged at the lowest point and this can be prevented by including intermediate dams within the pavement structure.

The design and construction of the pervious paving is dependent on the possible loading imposed by the expected traffic during its operational lifetime. Porous concrete and asphalt are not as durable and strong as the conventional structures and require fitting of geotextiles to minimize friction between layers. Guidance for the construction of pervious paving is given by the SUDS Manual (CIRIA 2007). The California Bearing Ratio (CBR) value used in the design of pervious paving should be measured (BS 1377:4:1990) or estimated for the saturated foundation soil (Jayasuriya and Kadurupokune 2008).

#### 7.3.2.3 Filter Strips and Swales

Filter strips are gently sloping areas of vegetated land in which runoff is directed. Filter strips are usually created between a hard surface area and a receiving stream and can be planted with grass or shrubs. These are designed to drain water evenly from impermeable areas and to filter out silt and other particulates. Vegetation is required to trap and remove pollutants and functions by naturally filtering surface runoffs and attenuates water flows.

Swales are shallow vegetated open channels (usually grassed) which channel runoffs from the surface to provide source control by infiltration and sometimes to store and drain discharges. Typically, swales are incorporated within a development, using sloping green space areas and roadside margins. Plants and grasses are grown within the channels to enhance pollutant removal efficiency. Swales can be part of a series of SUDS mechanisms which provide pre-treatment for runoff before water drains into the next system, such as a *retention pond* or an *infiltration basin* (Fig. 7.4). They typically form long shallow channels alongside a major road (Fig. 7.5); however, they can also be incorporated in landscaped residential areas and car parks (Fig. 7.6).

There are three types of swales: (1) *standard* swales; (2) *enhanced dry* swales; and (3) *wet* swales.

Standard swales (Fig. 7.7) are not engineered to provide the same pollutant reduction capacity as dry swales, which have filter medium or wet swales which function as an infiltration basin. Generally, swales remove pollutants introduced during frequent small storms. For larger storms of 10–50 % annual probability, they provide storage and act as a conveyance device for drainage. They are generally used for sub-catchments with small impermeable areas. The maximum impermeable catchment area for effective use of swales is about 2–4 ha. The soil (not coarse sand) should provide a stable bed for vegetation and groundwater must

**Fig. 7.4** Filter stripes, a swale and a retention pond at Campbell Park, Milton Keynes

**Fig. 7.5** A dry swale alongside a major road in Milton Keynes

be more than 1 m below the base of swales. Like infiltration basins, swales only accept slow water flows for a maximum slope of 10 % for effective infiltration and pollutant removal.

Swales receive direct rainwater or via runoffs from their edges and sides, or from kerb side off lets. Swales work by attenuating and reducing flow rates to allow sedimentation and infiltration of pollutants. Vegetation removes particulate matters and other pollutants. Furthermore, organic pollutants are also broken down biologically by microbes and plants.

**Fig. 7.6** A wet swale at Caldecotte near a car park in a residential area of Milton Keynes

**Fig. 7.7** A standard swale at Campbell Park in Milton Keynes

#### 7.3.2.4 Infiltration Trenches and Soakaways

These are subterranean structures excavated and filled with stones or other granular materials to provide a transient reservoir, to allow the infiltration of surface water runoffs to the ground. They can be trenches, basins (e.g., swales), or soakaways, where surface water runoffs can be temporarily stored then slowly percolated into the ground. Digest 365 (BRE 2007) provides guidance for soakaway design and a manual of good practice on infiltration drainage is provided by the Construction Industry, Research and Information Association (CIRIA) C156 (CIRIA 1996).

*Infiltration trenches* can act as linear drains consisting of trenches filled with permeable materials, to store and convey water and provide infiltration. A perforated pipe is commonly placed along the base of the trench to assist drainage. Infiltration trenches receive direct rainwater, flows from roadside edges, and from the immediate surrounding areas, see Fig. 7.8. They are specifically used by the *Highway Authority* for draining water off roads. Pollutants are removed by absorption, filtering, and microbial decomposition in the surrounding soil. Systems can be designed to successfully incorporate both infiltration and filter systems. Generally, stormwater flow into the trench gradually filters into the ground where it can then be pretreated using a filter strip, gully, or sump pit to remove excessive solids.

Infiltration devices, such as soakaways or infiltration trenches, provide considerable water storage. Furthermore, infiltration can improve runoff water quality before discharging into a secondary basin where biological breakdown of organic pollutants can occur.

**Fig. 7.8** An infiltration trench at a main road in Caldecotte, Milton Keynes

**Fig. 7.9** An infiltration pond in the residential area of Caldecotte, Milton Keynes

#### 7.3.2.5 Infiltration Basins, Swales, and Ponds

Infiltration basins (Fig. 7.9) are temporary water features which retain stormwater runoffs, reducing peak flows into watercourses. These provide infiltration of pollutants which can be deposited and absorbed into the soil substrate and allow microbial decomposition (USEPA 2000a; Barraud 1999) as well as allowing water infiltration directly into the ground (Winer 2000). Swales can be viewed as shallow ponds but are usually empty during dry periods, whereas ponds can contain water continuously and are often specifically designed to contain stormwater. Basins and ponds frequently accommodate vegetation such as reeds which provide further treatment of pollutants in surface water runoffs (Griggs and Grant 2000). Swales and ponds provide pleasant green areas and calming water features within a development. They can also provide ecological habitats for small animals, and in some cases, support recreational activities such as nature hobbies and provide children's play areas.

#### 7.3.2.6 Retention Basins, Ponds, Lakes, and Wetlands

Retention basins, ponds, and wetlands collect surface water runoffs from large drainage catchments via piped networks or from other SUDS upstream. These basins are planted with grass and are usually damp and boggy, except during rainy seasons when they are filled, allowing sedimentation of pollutants. Retention basins are also known as wet ponds or wet detention basins (Fig. 7.4) and on a larger scale, effluent water is drained into a lake (Figs. 7.10 and 7.12) or wetlands.

**Fig. 7.10** Caldecotte Lake in Milton Keynes

Ponds, lakes, and wetlands are designed to provide surface water runoff storage and allow storage of various levels of water during storms, enhancing flood-storage capacity and attenuating flow. Surface water can be conveyed via swales, filter drains, or piped systems. Ponds and wetlands can be permanent water bodies, planted with aquatic species to enhance amenity and biodiversity by providing habitats for wildlife in the urban areas. Ponds allow sufficient retention time for particulates and solids to settle, and not discharge into watercourses. Simultaneously, pollutants can be filtered and broken down biologically. Algae and plants in wetlands provide a good level of nutrient removal and filtration for pollutants. Lakes and wetlands provide a dual purpose enjoyed by water sport club members and nature enthusiasts.

## 7.4 SUDS Adoption, Survey, and Surface Water Management

The particular SUDS strategy is dependent on the soil type and characteristics of the groundwater tables in the area (Bregulla et al. 2010; CIRIA 2007). A survey of the ground conditions is essential before selecting the appropriate SUDS techniques for site drainage. The assessment should also include: a study of the ecological status and sediment releases in the area; the possible impact caused by flooding; the current status regarding drainage in the area including an assessment of possible pollution to soil and the water resource in the area.

The design and planning of SUDS requires stakeholder involvement. At a local level, the multifunctional benefits of SUDS will require involvement of: the developers, the designers and construction engineers, environmental consultants, and local authorities to develop a master plan for the site development, and finally to design and select the locations of SUDS devices (CIRIA 2007b). *Sewer operators* who provide the regulations and environmental infrastructures for SUDS, should be the principal consultees and if drainage to roads is involved, then the *Highway Agency* should also be included in the design and planning processes. Intuitively, surface water management is included in the *Code for Sustainable Homes* (CSH) for housing developments (CLG 2008).

The purpose of a scoping study is to assess the potential for incorporating SUDS into a site development which would contribute to surface water quality. A typical scoping study includes multiple subassessments, these include:

- An environmental assessment of the area, its geological condition (soil permeability and hydrology characteristics of the site), surface water runoff characteristics and wastewater drainage, ecological status, and sediment releases;
- An impact assessment of the land development (urban, domestic, commercial, industrial, mining, power generation, forestry, and agricultural), the density of the development, the required community services, including a consideration of the impact caused by waste discharges, contamination, landfill and abstraction have on the local water catchments, and river water quality;
- An assessment of the impacts caused by climate change and flooding scenarios;
- A cost-benefit analysis which looks at flood management, diffuse pollution, amenity, and biodiversity;
- An appraisal of the appropriate SUDS mechanisms for site development.

The drainage area should be downstream of any groundwater sources. It is important that the subsoil has percolation characteristics suitable for drainage. Examples of poorly drained or saturated soils are sandy clay, silty clay, and normal clay. In addition, examples of subsoils with good percolation characteristics are sand, gravel, chalk, sandy, and clay loam. *Reed bed treatment* or other constructed wetland treatment systems can also be used to provide secondary or tertiary treatments (see BRE Good Building Guide No. 42 (2001)).

### 7.4.1 Land Use and Adoption

Developers should engage relevant stakeholders, and most importantly, the local planning authorities and principal consultees (e.g., Environment Agency, water and sewer operators, and highway authorities) to consider a SUDS strategy serving the wider area, encapsulating a number of sites, such as introduction of an attenuation pond or a swale for a playing field or community amenity area (CIRIA 2004). The selection of SUDS devices and locations should also consider the development's runoff characteristics, the local and the regional areas, and whether the areas are prone to flooding where series of SUDS features, retention pond or wetland, with alternative routing of floodwater could be needed to cope with heavy rainfall. The Caldecotte lake business park (Fig. 7.11) is an example of such a development.

**Fig. 7.11** SUDS and water features at Caldecotte Business Park

Development density and layout could affect surface water runoff characteristics which are important factors when determining the scale and type of SUDS device to be included; these could have a significant impact on land use. At the planning stage, the sizing and siting of SUDS should be a part of the feasibility study. Land use is part of the *Regional spatial-planning strategy* (RSS) that controls the development of land in public spaces. Land use has an important social, economic, and environmental role to play within a development and also in the resultant residential community. Guidance on the planning, adoption, responsibility, and funding for SUDS maintenance is provided by the SUDS Manual (CIRIA 2007; CIRIA 2000; CIRIA 2004). There are many key considerations for local authorities who adopt SUDS, including:

- The use of open space for nature conservation, recreational activities, and for improving the esthetic value of the housing development should not be in conflict with the effectiveness of SUDS for management of surface water drainage;
- Health and safety issues relating to public hygiene and people's safety while living and working in the area;
- Long-term responsibility and maintenance of SUDS.

Adoption authorities (e.g., property owners, local authorities, highway authorities, and water and sewer operators) require independent assurance that the SUDS have been constructed in accordance with good design practices as outlined in the SUDS Manual C697 (CIRIA 2007) and CIRIA's site handbook (C698) for the construction of SUDS (CIRIA 2007c); and that conditions for handover are acceptable following inspection of the responsible authorities. Developers need to provide maintenance plans including any remedial work (e.g., dredging and cleaning) during the development phase and will be required in the future to advise on matters regarding any accumulation of materials like silt, which will need periodic clearing to ensure intended performance.

## 7.5 Maintenance and Management

Most SUDS devices can be maintained as a part of a standard landscaping contract issued by local authorities or the relevant landowner. Landscape maintenance can be adapted to include care of SUDS surfaces, involving wetland vegetation maintenance, grass and landscape maintenance, and silt management. For SUDS components such as drainage systems in pervious paving, filter trenches, soakaways and underground infiltration devices, regular maintenance by drainage engineers is essential. A maintenance plan should be in place so that routine removal of litter, plant waste, and silt to avoid clogging of various SUDS components. The likelihood of a SUDS strategy underperforming, or at worst, exacerbating water drainage, will depend mainly on quality of design, planning and construction, and particularly silt management. Retention basins predominantly retaining runoffs from roofs require less frequent clearing of silt, whereas for runoffs from roads containing high pollution and sediment loads would require frequent attention.

SUDS management strategies should also consider wildlife (Fig. 7.12). Therefore, maintenance manuals should provide clear guidance and warning to those

**Fig. 7.12** Caldecotte Lake in Milton Keynes

undertaking maintenance work to avoid breeding seasons and curb machinery use which could have detrimental effects to nestling birds or cause direct damage and destroy or obstruct access to the homes of protected species.

## 7.6 Conclusion

Due to the unfolding effects of climate change and environmental pressures on urban development, SUDS are now integral features for urban development. Their inclusion can help mitigate and manage surface and stormwater flow, which can provide social and economic benefits as well as being an environmental necessity. Selection and design of SUDS devices and techniques will depend on several factors, including: planning issues, water quality, water resources, architectural and landscape requirements, as well as ecology and amenity issues, and the need to meet the requirements for that particular development (e.g., housing, school, hospital, and commercial parks, etc). The selection tool should be based on surface water management train principles (see Sect. 2) and should include the following objectives:

- Drainage techniques should be used in series to provide a multifunctional approach to meet the design criteria of attenuating flow, reducing risk of flooding, improving water quality by filtration and absorption, preventing drying of soil, and recharging of groundwater;
- Surface water should be allowed to flow naturally to the watercourses by infiltration and to allow the natural functioning of the hydrological cycles. Artificial treatment of water should not be needed if the water is not contaminated;
- Wherever possible, the design and planning should give priority to prevention and source control at the top of the management train rather than regional control techniques downstream;
- Identify possible SUDS technique combinations to maximize drainage and water treatment performance;
- Minimize the use of impermeable surfaces in the development (except where necessary);
- Design should be sympathetic to meet local and environmental needs; this will require consultation of all stakeholder groups (e.g., local authorities, residents, businesses, public services, and other organizations). Esthetic design should accompany technical consideration and generate added value for the site, in cases where water features provide pleasing qualities (e.g., ponds or swales) this inevitably increases desirability and promotes higher property values;
- A robust maintenance plan should be put in place to keep SUDS clean, free from obstacles, and operational.

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# Chapter 8
# Urban Waste Management

**Li'ao Wang**

**Abstract** This chapter introduces the key themes concerned within waste processing, waste management ,and integrated waste management systems. It delves into the principle methods behind waste disposal, their advantages and disadvantages, and comments on the array of influencing factors placed upon central and local governments in delivering safe and sustainable systems to deal with society's increasing waste problems. A case study is included to demonstrate the main issues in a practical situation, where population increase, land use pressures, technical, and socioeconomic influences become inextricably interwoven; and how ensuring a safe means of dealing with humanities waste will become ever more challenging. *Learning outcomes*: On successful completion of this chapter, readers will be able to: (1) Have knowledge of basic waste management strategies and the waste processing cycle; (2) Appreciate the importance of an integrated approach to waste management and why many factors are intimately linked; (3) Have an awareness of the key technologies for waste disposal; and (4) Understand the waste management process in practice, through a case study.

**Keywords** Combustion · Composting · Landfill · Urban solid waste management

## 8.1 Introduction

Since production of waste is increasing at a high speed, an integrated solid waste management (ISWM) system which includes the reducing, reusing, recycling, and disposal of waste material, will play an important role in the world's sustainable

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development due to several benefits: (1) reducing the depletion of the earth's limited natural resources; (2) reducing pollution produced by discharging untreated waste; and (3) indirectly saving energy. At present, the ISWM (defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals) is considered to be an optimized waste management system where the environmentally and economically best solution is chosen for each case. This is without regard to the waste hierarchy (Sundqvist 1999) and is key for successful municipal solid waste (MSW) treatment (Hu et al. 1998).

Some advanced industrial countries, such as Germany, Sweden, Japan, and the United States, have achieved remarkable results in resource comprehensive utilization and solid waste management. There have been a lot of changes in solid waste management strategies including composting, combustion, and landfill, which are applied to treat and dispose waste across the world. However, with societal development, one revolutionary change was that solid waste management begins with reduction—using less to start with. In addition: reuse and recycle. Especially, incinerating and composting organic waste became dominant methods of solid waste treatment, instead of disposal by landfill.

## 8.2 Definitions and Concepts

### *8.2.1 Definition of Solid Waste Management*

The discipline of Solid Waste Management (SWM) is associated with the control of waste generation, storage, collection, transfer and transport, processing, and disposal of solid waste in a manner that is in accordance with best principles of public health, economics, engineering, conservation, esthetics, and it is the response to the public requirements. SWM includes all administrative, financial, legal, planning, and engineering functions which are involved in delivering solutions to all problems concerning solid waste.

The functional elements of SWM are principally waste generation, waste handling and separation, storage and processing at source, collection, separation, and processing and transformation of solid waste, transfer, and transport and disposal.

### *8.2.2 Sources of Solid Waste*

There are several main sources from which solid waste originate, these include: residents, commerce, institutions, construction and demolition, municipal services (excluding treatment facilities), treatment plant sites, municipal incinerators, industry, and agriculture. Table 8.1 provides some supporting examples within these source categories.

**Table 8.1 Sources of solid waste**

| Source | Sub-source | Waste |
|---|---|---|
| Residential and commercial | Homes, offices, light commercial units | Organic: food waste, paper, plastics, textiles, rubber, leather, wood, and garden waste<br>Inorganic: glass, crockery, tin can, aluminum, ferrous metal, and dirt |
| Institutional | Public sector: schools, prisons, and hospital | Organic and inorganic as above but no waste from manufacturing or clinical waste |
| Construction and demolition | Private construction companies | Mix of waste types: rubble, dirt, stone, concrete, bricks, plaster, lumber, shingle, and plumbing, heating, and electrical parts |
| Municipal service | Local authorities | Mix of waste types: street sweeping waste, road side litter, waste from municipal litter container, landscape and tree trimmings, catching basin debris, dead animal, and abandoned vehicles |
| Treatment plant wastes and other residues | Water treatment plants and industrial waste treatment facilities | Mix of waste types: Dangerous toxic chemicals, heavy metals, and residues of municipal incinerators such as ashes |
| Agricultural waste | Private and public farms | Mix of waste types: Chemical and biomass waste from planting and harvesting fields, trees and vine crops; horticulture; milk production; deadstock(dead animals) and operation of feedlots. Fertilizer, machinery, oil, slurry, farm buildings and housing, plastic bags, and bale wrapping |
| Special waste | Households, commerce and light industry | Mix of waste types: Bulky items, consumer electronics, white good, garden waste that is collected separately, batteries, oil, and tires from residual and commercial waste |

### *8.2.3 Classification and Distribution*

Classifying collection of municipal solid waste (MSW) is one of the key steps for ISWM. The classification process means that the MSW is first classified into several different groups such as composting materials (food refuse), combustible materials (fiber and paper), and recycling materials (metallic and glass). Once classified, these different waste types are then collected and forwarded to the appropriate processing unit.

The introduction of waste distribution centers is necessary because disposal sites for solid urban waste, is often located far from populated areas. In addition, such centers also facilitate financial savings, traffic access, and materials recovery. There are three main types of waste distribution center: direct load, storage load, and combined direct and discharge load.

## 8.2.4 *Urban Waste Management Methods (Li et al. 2007)*

### 8.2.4.1 Composting

Composting is a process which is controlled by using microorganisms such as bacteria and fungi, which exist in nature to transform certain organic materials into biologically stable materials (called *humus*). The production of this process is called composting.

According to the amount of oxygen required by the microorganism during the composting process, composting can be divided into two types: aerobic composting and anaerobic composting. Aerobic composting happens on the condition that microorganisms are exposed to air (i.e., in the presence of oxygen). A series of exothermic decomposition reactions then occur, transferring the organism into simple and stable humus. While anaerobic composting or anaerobic digestion is common place within nature, in waste situations where organisms are exposed to water and limited quantities of oxygen, anaerobic microorganisms convert the organisms (within the waste) into $CH_4$ and $CO_2$ gas, methane and carbondioxide respectively. The resulting particles of compost are fine in texture with a dark brown appearance, have a pH between 7 and 9, and can be sweet smelling. Compost in this state can now be used as land fertilizer.

#### Aerobic Composting

There are multiple factors which necessitate successful aerobic composting. This section simply describes a few, these include: (1) oxygen, the key component which helps organism degradation, exothermic reactions take place and water evaporation can often be seen in the form of steam; (2) water, another key component that often determines fermentation speed and compost maturity, 50–60 % content is ideal to encourages decomposition; (3) temperature, ideal levels fluctuate between 50 and 60 °C, as temperature increases so does decomposition, but also some ova, pathogenic bacteria, and weeds are killed, rendering it safe to use on farmland; (4) organic content, ideal temperatures are unmaintainable when content is insufficient (20–80 % ideal) which results in poor fertilizer quality; (5) particle size, this influences the ventilation potential and hence the oxygen quantity, ideal particle size is between 25 and 75 mm; (6) carbon/nitrogen ratio, low ratios cause bacteria autolysis, nitrogen waste and low enzyme production, whereas high ratios encourage bacterial infection, so the better ratio is 20–30:1; (7) other factors, these include porosity during composting which should be around 35–50 %, pH value (ideal 7–7.5) and seeding ratio (ideally 1–5 %).

Through composting, the humus and nutrient content in the soil will increase. Besides, some organic matters found within compost can combine with soil and loosen it (in the case of clay soils) and encourage sandy soils to form particles which improve its quality characterized by better soil structure, greater ventilation, and water retention of the soil. Meanwhile, some essential plant nutrients can be supplied, however these nutrients cannot acts as a fertilizer substitute. Interestingly, composting can also store nutrients for plants, allowing long-term availability to plants.

Although composting is ideal to cope with solid urban waste problems, although the process is relatively simple and used for agriculture, it brings some environmental problems too. Odor is an issue that often encompasses unpleasant smells, requiring carefully located composting sites. Pollution from heavy metals can occur if soluble metals dissolve into the water and permeate into the ground. Although compost can provide plant nutrition, it can contain heavy metals, in which case it ceases to replace fertilizer and farmers naturally become wary of its use. Finally, issues of cost and investment come into question, which largely determines whether sites operate efficiently or if sites can be developed.

#### 8.2.4.2 Combustion

Waste combustion is the thermal processing of solid waste by chemical oxidation during stoichiometry or with excess quantities of air. Combustion of MSW has already become a basic treatment method due to the obvious advantages associated with volume reduction and relatively harmlesness. The mechanical subsystems of a large combustion system include: (1) a feed mechanism with an unloading platform, storage pit, overhead crane, and feed cute; (2) the combustion area itself which has a grate, combustion chamber, and other auxiliary components; (3) residue treatment which requires a quenching tank, residue conveyor belt, metal recovery method, residue pit, and overhead crane; (4) exhaust treatment, this can include a secondary combustion chamber, cyclone, scrubber, bag-house, stack, and ash solidification; and (5) energy recovery, featuring a boiler, and turbine generator.

The result of solid waste combustion is influenced by many different factors because the combustion process itself is very complex and contains a lot of physical and chemical reactions. For example, incinerator types, characters of waste, particle size, temperature, time, and oxygen supply inextricably interwoven.

From this list, character of waste is the decisive factor to gage whether the waste is fit for combustion and how effective combustion will be. Temperature is also crucial to limit exhaust emissions.

Although the advantages of combustion have been highlighted it also has many disadvantages, such as exhaust emission. There are some toxic and harmful substances in the exhaust emissions, such as dioxin, fly ash (which belongs to hazardous waste), acid gas, soot, and malodor (mainly composed of organic sulfide or nitride). There are a few remedies to these issues. For malodorous, there are several treatment methods; for example, combustion, catalytic combustion, absorption, adsorption, microorganism decomposition, and condensation. The addition of alkaline solution can help to absorb acid gas, and excess air (oxygen) can be combusted in the secondary combustion chamber to reduce soot quantities.

### 8.2.4.3 Pyrolysis (gasification)

Pyrolysis (gasification) is the thermal processing of waste in the complete *absence* of oxygen (partial combustion). At extreme temperature and where the oxygen level is negligible, the unstable organic substance split, through a combination of thermal cracking and condensation reactions into gaseous, liquid, and solid fractions. In summary, the key differences between combustion and pyrolysis (gasification) are that combustion occurs in the presence of oxygen (excess), an exothermic reaction happens, resulting in the production of water, carbon dioxide, and non-combustible residue. Comparatively, pyrolysis is 'essentially' oxygen free, an endothermic reaction happens which produces combustible gases, liquid, and carbon tars.

### 8.2.4.4 Landfill of Solid Waste

Traditional open dump sites are generally located in the outer suburbs, in an industrial zone, brown field location, valley, or often near a river (Fig. 8.1) where there is limited pollution control. Therefore, as one might expect, many environmental problems originate around open dumping sites. *Leaching* (liquid waste) causes water and soil pollution, odors reduce air quality, and in warm climates dumps harbor flies, mosquitoes, rats, and mice, which spread diseases. Unfortunately, open dumps frequently occupy large areas of land. Another, and more controlled dumping ground, are landfill sites. Landfill sites are areas where residual solid waste finally circum to rest, buried under ground in the surface soil. Compared with open dumps, landfill has a management system and applies effective technical measures to prevent water, soil, and air pollution caused by leachate and toxic gases. Coupled with these significant benefits, it can also reduce negative impacts on public health security and environment during the lifecycle of the landfill site.

**Fig. 8.1** Landfill scenery

A multitude of chemical and biological reactions occur in landfill sites. The biological reactions include aerobic decomposition and anaerobic decomposition with the production of leachate and landfill gas such as $CH_4$, $CO_2$, $NH_3$, $H_2S$. Similarly, chemical reactions include dissolution, evaporation and vaporization, sorption, decomposition, and oxidation-reduction reactions.

*Leachate* is a type of liquid that 'leaks' form waste and gathers at the base of landfill sites. This liquid is either found originally within the waste, or it is produced after rain water mixes with chemical waste. Modern landfill sites are often designed to prevent leachate from leaching out and entering the environment with an impermeable system. However, if not properly managed, the leachate risks leaking from the site and permeates groundwater near the site, often with disastrous consequences.

Leachate composition varies, but it primarily consists of organic pollutants, including *arenes* (aromatic hydrocarbons), alkanes and acids, esters, and other organic pollutants. Needless to say, leachate is highly toxic.

Management techniques include lining systems, leachate collection and extraction systems, landfill gas collection, and extraction systems, covering layers that are uses on a daily basis and final cover layers.

Landfill lining systems use a permeable sheet material to line the bottom of a site, similar in arrangement to a domestic 'pond liner' but on a much larger scale. It is used to minimize infiltration of leachate into subsurface soils below the landfill site, thus reducing the potential for groundwater contamination. There are many kinds of lining materials, such as geotextiles, geomembrances, and geonet. Besides these, compacted clay, sand, and gravel can also be used as lining materials.

Figure 8.2 shows a leachate collection system which prevents leachate leaking into unwanted areas and collects it in channels which use gravity to encourage flow. Throughout the landfill area, a primary and secondary liner system ensures that leakage is minimized through a leak detection system and secondary collection channels.

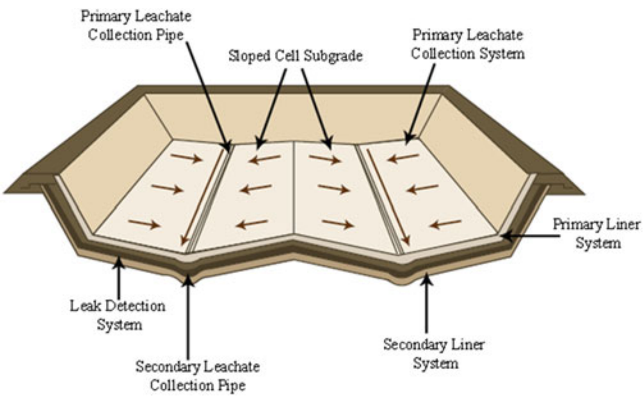


**Fig. 8.2** Leachate collection system

Leachate Treatment

The collected leachate finally flows into a municipal wastewater treatment plant. During this process it can be treated exclusively with biological methods or by physical and chemical methods first, before going onto the biological method.

Surface Water Management

Minimizing surface water runoff entering the site hugely helps in reducing leachate quantity. This can be achieved through drainage devices (see chapter XX) such as swales, drainage trenches, stormwater storage basins, intermediate cover layers, and top cover layer.

Landfill Gas

There are five phases during which landfill gases are created: (1) initial adjustment phase, aerobic biological decomposition occurs; (2) transition phase, ocurs when oxygen is depleted and anaerobic conditions begin to develop; (3) acidic phase; (4) methane fermentation phase; and (5) the maturation phase. The gases mainly include methane ($CH_{4,}$ which occupies 45–60 %), carbon dioxide ($CO_2$, 40–60 %), nitrogen gas ($N_2$, 2–5 %), oxygen ($O_2$, 0.1–1.0 %), and ammonia ($NH_3$, 0.1–1.0 %). Typical yield of landfill gas is about 3–90 L/kg dry. Passive control, active control with perimeter facilities, and active control with vertical and horizontal gas extraction well are utilized to control the gas.

'Passive control' uses landfill gas pressure as the driving force to create gas flow. Whereas 'active control' uses gas extraction wells and trenches located at the site perimeter to create a partial vacuum. Active control also can incorporate vertical and horizontal gas extraction wells to effectively extract landfill gas. The extracted gas can either be flared off or used productively as fuel to power a generator to produce heat or electricity.

Once landfill sites have reached their productive capacity, steps should be taken to securely close them, this is termed 'landfill closure'. After landfill closure, post-closure care plans should be put in place which involves long-term monitoring and maintenance of closed sites. Furthermore, monitoring should encompass groundwater and air quality measurements to satisfy robust control procedures.

## 8.3 Case study

A detailed case study is included to demonstrate the waste process, from generation, collection, transportation, to treatment. The case study describes a situation in Chongqing, China, which is typical of other waste processing across China nowadays.

### 8.3.1 Background

As one might expect, China's economic growth has raised living standards for millions of inhabitants, however development has been detrimental to the ecology and environment, and has increased waste significantly. The dual influences of resource supply and ecological protection pose a significant challenge to China's sustainable development (Qi 2004; Su and Wang 2003).

Chongqing is located in Southwest China,it is the nation's fourth municipality with nine districts. The main urban area covers about 5,400 km$^2$ with a population of about 4.5 million people.

In the last century, most of the MSW was piled along the Yangtze and Jialing riversides, dumped directly into them or just minimally treated. This caused subsidiary issues which were harmful to sanitation and the wider environment such as leachate. The recent completion of the Three Gorges Reservoir near the two rivers, now means that a successful integrated solid waste management strategy is vital.

### 8.3.2 Generation and Characteristics of the Urban Solid Wastes

The average daily waste quantity is approximately 4,275 tons, equating to 0.95 kg per person (Hu 2009). Waste composition is mainly domestic refuse, road cleaning refuse and institutional refuse (official business, schools and service industries), as well as a small amount of construction refuse. Table 8.2 shows district waste composition(Wang and Pei 2009).

It is clear that food waste constitutes the largest proportion at 59.2 % followed by plastics, paper, fiber, wood, glass, metal, and rubber. The metal content of solid waste generated in the Shapingba district is higher than the other two sites.

The characteristics of urban solid waste (USW) composition at the main districts in Chongqing are shown in Tables 8.3 and 8.4. Investigation showed a considerable decrease in combustibles and ash content, while the percentage of fiber and paper has increased over the years.

**Table 8.2** Composition of urban solid waste in Chongqing's main districts (%)

| Location | Paper | Fiber | Plastic | Rubber | Wood | Food refuse | Metal | Glass |
|---|---|---|---|---|---|---|---|---|
| Yuzhogn District | 10.0 | 6.1 | 18.3 | 0.4 | 4.4 | 58.5 | 0.1 | 2.2 |
| Jiangbei District | 9.6 | 6.6 | 15.2 | 0.0 | 5.1 | 57.8 | 0.7 | 4.9 |
| Shapingba District | 10.6 | 5.5 | 13.5 | 0.4 | 3.0 | 61.4 | 2.4 | 3.2 |
| Average | 10.1 | 6.1 | 15.7 | 0.3 | 4.2 | 59.2 | 1.1 | 3.4 |

**Table 8.3** Characteristics of urban solid waste

| Characteristics | 1998 (Li and Gu 2001) | 2006 |
|---|---|---|
| Food refuse percentage (%) | 69.3 | 55.4 |
| Paper and fiber percentage (%) | 6.5 | 14.6 |
| Specific Weight (Kg/m$^{3)}$ | 470 | 310 |
| Combustibles (%) | 37.1 | 25.4 |
| Ash content (%) | 16.31 | 9.6 |
| Moisture content (%) | 53.6 | 62.3 |
| Net calorific value (kJ/kg) | – | 3,876 |

**Table 8.4** Typical distribution percentages of components in residential MSW for low, middle and upper-income countries excluding recycled materials

| Component | Low-income countries | Middle-income countries | Upper-income countries |
|---|---|---|---|
| Food waste | 40–85 | 20–65 | 6–30 |
| Paper | 1–10 | 8–30 | 20–45 |
| Cardboard | | | 5–15 |
| Plastics | 1–5 | 2–6 | 2–8 |
| Textiles | 1–5 | 2–10 | 2–6 |
| Rubber | 1–5 | 1–4 | 0–2 |
| Leather | | | 0–2 |
| Yard waste | 1–5 | 1–10 | 10–20 |
| Wood | | | 1–4 |
| Misc. organics | – | – | – |
| Glass | 1–10 | 1–10 | 4–12 |
| Tin cans | 1–5 | 1–5 | 2–8 |
| Aluminum | | | 0–1 |
| Other metal | | | 1–4 |
| Dirt, ash, etc. | 1–40 | 1–30 | 0–10 |

*Source* Tchobanoglus et al. 1993

### 8.3.3 Urban Solid Waste Management

There are national and regional waste regulations in China; Chongqing's solid waste management consists of two administrative sections: (1) the Chongqing Environment Protection Bureau (CEPB) that regulates the management of industrial solid waste; and (2) the department under the Chongqing Municipal Administration Commission (CMAC) that takes the responsibility for the management of the MSW. Essentially, the solid waste management system includes collection sites, transfer stations, recycling, and final disposal. This is undertaken by a private company, authorized to manage Chongqing's properties as well as licensed to operate the cleaning, transferring, and disposing of urban solid waste through various facilities in the main districts.

#### 8.3.3.1 Collection System

Source-separated collection of household waste is helpful for ISWM. After waste is separated, it is collected and distributed for further processing by different sectors. Unfortunately, source-separated collection at the household level has not yet been implemented successfully in Chongqing. In 2012, the following collection systems apply:

(1) Residential refuse: households put their daily refuse into a nearby container that is collected and delivered to a waste collection station, managed by a residential committee or a sub-region's management department. The Environmental Sanitary Protection Division of the Chongqing Municipal Administration Commission (CMAC) then transports this refuse to treatment sites. In certain cases (large residential regions), refuse is collected and sent directly to treatment sites by a land management company.
(2) Institutional refuse: collection and transportation of institutional refuse is the responsibility of the individual institution. They can manage transportation themselves or outsource this responsibility to a professional 'environment and protection company' which undertakes waste disposal.
(3) Commercial refuse: At most food markets in Chongqing, produce is often delivered directly from local farms and involves little packaging; therefore, refuse always contains a high proportion of organic matter. A proportion is reused in animal feed stuffs and the rest is collected by market's management and is sent directly to treatment sites.
(4) Street refuse: Cleaning of roads, public places, and associated waste disposal is the responsibility of a particular department under CMAC. Waste is initially collected and transported into nearby containers and then sent to treatment sites.
(5) Construction refuse: Recyclable or reusable waste material is sent directly by the construction company to treatment sites for processing. Unrecyclable material is also handled by construction companies and is sent to processing plants and dealt with accordingly.

Certain households in larger residential areas are required to source-separate their waste before collection. In 2002, waste packaging accounted for 68 %, but waste bins on streets did not provide people with source-separation facilities. However since 2002, the government has made some attempts to encourage residents to source-separate their waste by providing the necessary facilities at waste disposal sites. In some areas of Chongqing (e.g., Shapingba District), waste containers were completely redesigned and featured two waste disposal sections instead of one: one for recyclables and the other for non-recyclable waste, distinguished by different container colors and labeling.

#### 8.3.3.2 Treatment and Recycling

Treatment

Approximately 37 % of all USW in Chongqing is incinerated for power generation; only 1.8 % is composted, about 61.2 % goes to landfill of which half is used for power generation from resulting methane gas. Table 8.5 shows the proportional distribution of waste in Chongqing. The restaurants waste disposal plant was built in 2011.The organic matter used for power generation by anaerobic fermentation, while the oil from the dining table for production of bio-diesel.

Recycling

The recyclable materials in Chongqing's MSW are paper, plastic, and metal. Each recyclable beer bottle is worth about ¥0.1–0.2 (US$0.015–0.03), aluminum soda cans ¥ 0.05 (less than US$0.01), and plastic bottles ¥ 0.05–0.1 (US$0.01). In addition, waste paper or magazines are worth about ¥ 0.2–0.4 (US$0.03–0.06) per kilogram. These materials are often collected at source, in waste bins by poor people, or reusable waste collectors who patrol different residential areas. After official collection, these items are sent to factories for recycling.

Composting

Although composting makes use of organic waste, in general, the practice is not taken advantage of in Chongqing due to several market reasons: (1) obtaining organic waste from source-separated waste is limited and capital investment required for equipment will initially mean that compost would be more expensive than fertilizer; (2) public perception of compost use is unfavorable, especially from farmers who resist its use having originated from waste; (3) commercial demand for compost is low, as use would be restricted to non-food applications such as planting; and (4) strict regulation concerning compost use severely restricts its potential due to possible secondary polluting issues. These key reasons make composting unrecommendable (Zhang and Li 2000).

**Table 8.5** MSW treatment sites in Chongqing

| Location | Changshengtaqiao Landfill | Heishizi Landfill | Tongxiang incineration plant | Compost | Restaurant disposal plant |
|---|---|---|---|---|---|
| Capacity (t/d) | 1,500 | 1,000 | 1,500 | 50–80 | 1,000 |

### Incineration

There is a modern incineration plant located in the Beibei District that has an incineration capacity of 1,500 tons per day and a 2 × 12,000 kW electricity generation facility. The plant is equipped with two grates that are suitable for waste with a higher moisture content, which a higher percentage of incombustibles are, and waste with a lower net caloric value. It can generate about 405 MWh per day. A pollution control system, Semi-dry technology, ensures that exhaust discharge meets both Chinese and European standards for MSW incineration.

### Sanitary Landfill

To provide an idea of the scale to which waste generation causes, the following facts and figures speak for themselves. One sanitary landfill site was completed in June 2003 at a total investment cost of £48 m. The site covers 168 acres, has a capacity of 1,500 tons per day, was designed for a 20 year life span and serves five of the nine districts. Landfill gas, methane, is captured and used to power generators for electricity. A second site, in the north, serves the other districts and has a capacity of 1,000 tons per day. After five years of operation, of its 25 year lifetime, it is expected to generate sufficient methane for power generation.

### Waste Challenges

As urban sprawl continues, older landfill sites, which were once located in the peripheries, find new residents living close by. Such sites typically have poorer management and detrimental effects (e.g., leachate) can easily pollute the environment. As pressure increases for residential homes, older sites close and the land use is changed highlighting problems concerning the recovery and stabilization of landfill sites so that the land can serve a new purpose.

Composition characteristics of Chongqing's urban solid waste result in three main problems when considering processing by incineration: (1) high moisture content and low caloric value, this leads to unstable incineration; (2) low cost benefit, as shown in recent economic analysis; and (3) incinerator ware, high moisture content in waste has a tendency to erode incineration system components, resulting in landfills being the most effective and efficient means of disposal.

One key disadvantage of landfill is the significant site area requirement in light of growing demand for housing. This conflict subsequently means that waste incineration is fast becoming a more attractive method to deal with the vast quantities of waste. The local geography produces low annual wind speeds because of a hilly topography, this is problematic if incineration becomes commonplace as emissions containing dioxins and fly ash need to be removed by high level air movement. Resulting air quality will suffer, placing additional burden on an already smoggy local atmosphere. It is obvious that more stringent pollution controls will be required.

The low combustibility and caloric value of the urban solid waste is, in part, caused by the separation of waste conducted by scavenging poor people and reusable waste collectors at refuse disposal sites. Paper, plastics, and other combustible wastes are taken, leaving a high proportion of non-combustibles. On one hand this is beneficial through recycling efforts, on the other, consequential low combustible waste content reduces viability (Liu 2003). Not only do scavengers increase their susceptibility toward disease and infect, while collecting waste with economic value like paper and beer bottles, they leave toxic waste like batteries which leak and cause serious environmental harm. Unfortunately, this informal waste recovery behavior makes it challenging to regulate and implement an efficient and standardized waste treatment system. This challenge is experienced by other areas in China (Chung and Poon 1998), countries such as India (Sudhir et al. 1996).

By the end of 2010, MSW disposal reached 95% capacity in the main districts of Chongqing; this will only worsen with population increase. In fact, forecasts estimate that 6000 tons per day of USW should be expected. The lack of standby disposal capacity will be a problem in the future due to land use pressures, coupled with poor quality waste for incineration and low demand for compost. This problem is not likely to be solved easily, or quickly.

## Waste Solutions

To meet the needs of a fully functional and integrated solid waste management system in the future, the following aspects should be considered:

### Source-Separated Waste

The different districts have different economic situations, therefore effective separation and collection of solid waste materials must require different approaches. Source-separated waste practices must also become mandatory as this reduces the amount of solid waste and facilitates recycling of materials as well as reducing overall costs. Organic waste should particularly be separated to ensure effective composting and reduce moisture content in waste presented to incinerators, which in turn, increases efficiency and cost-effectiveness of plant operation.

Strictly regulate waste collection: formalizing waste collection systems has a multitude of benefits. This can provide paid jobs to the once scavengers, reduce disease and increase public health, ensure minimum combustibility waste content, lead to quality compost, and generally increase the economic potential from organized waste management.

Integrated approach: the facets of a successful IWMS are closely interconnected, with many knock-on effects. For example, source-separated waste means incineration systems are more viable which increases their uptake which reduces landfill requirement which means more homes can be built, reducing poverty and increasing living standards. Although this process is crude and simplified, it demonstrates the point. Coping for an increasing population is essential whereby land use and economics play a key role in the future.

## 8.4 Summary

This chapter has introduced the basic concepts of SWM and the benefits of an ISWM. It describes the key stages of the waste cycle, principally waste generation, collection, transportation, and final treatment and disposal of the waste. The four key waste treatment methods include composting, combustion, pyrolysis (gasification), and landfills; these are all explained in detail. In addition, the influencing factors and their advantages and disadvantages are also described. Composting uses microorganisms to transform organic waste into biologically stable 'humus', which has fertilization properties. However, compost quality depends on chemical content which can vary and deter farm usage. Combustion is the controlled burning of solid waste in the presence of excess air (oxygen). This has already become a basic treatment method because of volume reduction, nevertheless some toxic and harmful substances are released during combustion (e.g., dioxin, fly ash, acid gas, soot, and malodor). Landfill essentially involves burying waste, and in best practices, collecting resulting landfill gases (e.g., methane) and using it for power generation. Compared with open dumps, landfill is far more controlled and reduces water, air, and soil pollution caused by leachate and toxic gases.

A case study (Chongqing, China) demonstrates waste management in practice and the need for an integrated approach to address the interconnected issues surrounding waste, society, technology, and economics. As China and other developing countries continue to place huge demands on Earth's natural resources and land use (as populations and economies soar), successful waste management strategies will become ever more important.

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# Chapter 9
# Design of the Indoor Environment

**Ken Parsons**

**Abstract** This chapter presents knowledge of how people respond to the physical environment and how that is used in the design of indoor environments. It considers thermal, acoustical, visual, air quality, and vibration environmental components and their interaction and integration. It identifies the important physical factors that determine human response, and hence those that should be considered in environmental design. It also describes how people respond to each of the environmental components, environmental indices, and subjective scales that can be used to construct and carry out an environmental survey for assessing the quality of existing indoor environments. *Learning outcomes*: On successful completion of this chapter, readers will be able to: (1) Understand the important physical factors that should be considered in environmental design; (2) Gain insight into how people respond to the thermal, acoustical, visual, air quality, and vibration environments; and (3) Appreciate how to use human responses to design optimum indoor environments.

**Keywords** Air quality · Environmental design · Environmental survey · Noise · Thermal comfort · Subjective responses · Vision and lighting

## 9.1 Introduction

This chapter considers how to design indoor environments taking account of human response. It includes thermal, acoustical, visual, air quality, and vibration environments as well as their interactions and integration. It is important that

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indoor environments are designed to ensure that people are comfortable and satisfied, that they are stimulating and pleasant and that tasks and jobs can be carried out without loss in performance, or even enhancement to it. They must also promote a feeling of wellbeing and not cause problems to health. How such environments are created is an art and a science; however, much is known about how people respond to the physical environment and what can be considered optimum conditions, as well as how to assess and evaluate them. This chapter describes human responses to the environment and the specification and methods for the assessment of the environment that takes account of the responses of people.

## 9.2 Human Response

The continuous and changing response of people to their surrounding environment is part of the human condition. There is not a situation where a person is not surrounded by an environment, and it is therefore a continuous challenge to maintain health and comfort. The human body has many mechanisms for responding to environmental change. These can be physiological (e.g. sweating when hot) or behavioral (e.g. moving to a 'better' environment, opening a window etc.). The environment which people continuously occupy is also interactive and integrated. It comes in different forms (related to energy) and is detected in different ways by the body. Noise, thermal environments, and light all exist as part of the whole and the body has ears, nerve endings in the skin, and eyes to detect them. We could call these 'environmental components' (noise, light etc.) and each will vary in its level and nature. The energy content, level, and type (e.g. noise frequency) will all define the nature of an environmental component to which people are exposed at any one time.

It is important to recognize that the perception, severity, and influence that an environmental component will have on a person, will not be monotonically related to the physical quantity. That is to say, there is a 'human response transfer function' in engineering terms. For example, for a given level of noise, people are more sensitive to some frequencies than others. It is the nature of the physical environment and the human response to it that must be taken into account when designing an environment. This will be different for each environmental component and it is the total integrated environment that will elicit a 'whole person' response. It is the whole person response that will determine comfort, pleasure, dissatisfaction etc., with the environment (Parsons 2000; Wilson and Corlett 2005).

### *9.2.1 Measurement of the Physical Environment*

The response of a person to the environment will be influenced by the nature of ‘human sensors’ (e.g. eyes, ears etc.) as well as experience with the environment, mood, and other human characteristics. The human body is often sensitive to rate of change of the physical environment as well as its absolute value; it is therefore not a good measuring instrument. Physical instruments are therefore required to quantify the physical environment.

Instruments for measuring the environment should be selected according to appropriate specifications and standards (ISO 28802 2012). Particular considerations will include range, accuracy, sensitivity, and physical robustness. Calibration procedures will be necessary to ensure that the instruments measure according to the specification.

### *9.2.2 Measurement of Human Response*

Human responses to an environment can be both physiological and behavioral. People can also provide subjective responses. The physical environment to which people respond is often termed the *stress* on a person and the response to it is often termed the *strain*. Physiological responses would include a reduced blood flow in the extremities (vasoconstriction), such as the arms, hands, and feet. This will reduce heat loss when temperatures fall. It will cause a drop in skin temperature which is a physiological measure that can be interpreted as being related to feelings of ‘cold’. Temporary threshold shifts in response to loud noise; pupil diameter changes in response to light etc.: are all physiological measures. If we are to use physiological measures to identify environmental response and use in the design and evaluation of indoor environments, then we must have a method of interpreting the response to predict comfort, satisfaction, and so on.

Behavioral measures are particularly useful when the person measuring human response does not wish to influence or interact with the people being measured. People will move away from uncomfortable environments if there is an ‘adaptive opportunity’ to do so. They may not turn up for work; exhibit irritation; be easily distracted; adjust clothing; erect screens; open windows; turn off heating and so on. All of these behaviors can be quantified. It may be difficult to relate to cause and effect, however, as the reason for the behaviors must be considered.

Subjective measures quantify the responses of people to an environment, usually using subjective scales. Such scales are based upon psychological continua (or constructs) that are relevant to the psychological phenomenon of interest (e.g. hot, cold, bright, annoying etc.). The scales will be particularly useful in evaluating existing environments, in environmental surveys, and in post occupancy questionnaires (Parsons 2005a).

## 9.3 The Environmental Index

An *environmental index* is a mechanism for specifying environmental stress by integrating factors relevant to human response into a single number in such a way that the number varies with the strain on the person. In this way, optimum indoor environments can be specified in terms of the index value, rather than with a multitude of factors, which is cumbersome. Indices used to specify indoor environmental conditions for each environmental component are described below.

### *9.3.1 Indoor Thermal Environments*

People react to heat and cold by attempting to maintain their internal body temperature at around 37 °C. If this requires sweating to lose heat as conditions become too hot, or lowering skin temperature by vasoconstriction to preserve heat when conditions become cold, then a person will survive, but will be uncomfortable. The factors that influence human response and define thermal stress on a person are: air temperature, radiant temperature, air velocity, and humidity. Optimum indoor environmental conditions must be defined in terms of the interaction of those factors, so all must be considered. The particular combinations of the environmental variables that provide comfort will depend upon the clothing worn by the person and the level of activity, and hence, metabolic heat production of the person (Parsons 2003; Parsons 2005b).

Indices used to specify indoor environments integrate the six factors described above. For cold conditions, a calculation of the clothing insulation required (IREQ) is used to specify and assess work in freezer rooms for example (ISO 11079 2007). In hot conditions, a calculation of the sweating required (SWreq) is used as an index (PHS; ISO 7933 2004) (PHS is Predicted Heat Strain). Within these extremes, the predicted mean vote (PMV) index is used with the associated predicted percentage of dissatisfied (PPD) index (ISO 7730 2005). Local discomfort caused by draughts for example is also important and can be predicted from air temperature and air velocity as well as degree of turbulence (See ISO 7730 2005).

### *9.3.2 Predicted Mean Vote and Predicted Percentage Dissatisfied*

To provide a method for evaluating and analyzing thermal environments, Fanger (1970) made the proposal that the degree of discomfort will depend on the thermal load (*L*). This he defined as: '*the difference between the internal heat production and the heat loss to the actual environment for a man hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual* *activity level'*. In comfort conditions, the thermal load will be zero. For deviations from comfort, the thermal sensation experienced will be a function of the thermal load and the activity level. This provided an equation for the predicted mean vote (PMV) of a large group of subjects if they had rated their thermal sensation in that environment on the following scale (see ISO 7730 2005).

| | |
|---|---|
| Hot | +3 |
| Warm | +2 |
| Slightly warm | +1 |
| Neutral | 0 |
| Slightly cool | −1 |
| Cool | −2 |
| Cold | −3 |

The predicted percentage of dissatisfied (PPD) provides practical information concerning the number of potential complainers.

$$PPD = 100 - 95\exp - \left(0.03353PMV^4 + 0.2179PMV^2\right) \qquad (9.1)$$

ISO 7730 (2005) (Fig. 9.1).

Fanger (1970) describes a method for the use of the PMV and PPD in practical applications and includes examples involving an analysis of a large room and the use of: a thermal nonuniformity index, lowest possible percentage of dissatisfied (LPPD), indicating the 'best' that can be achieved by changing the average PMV value in the room only– (e.g. by changing average air temperature), and hence

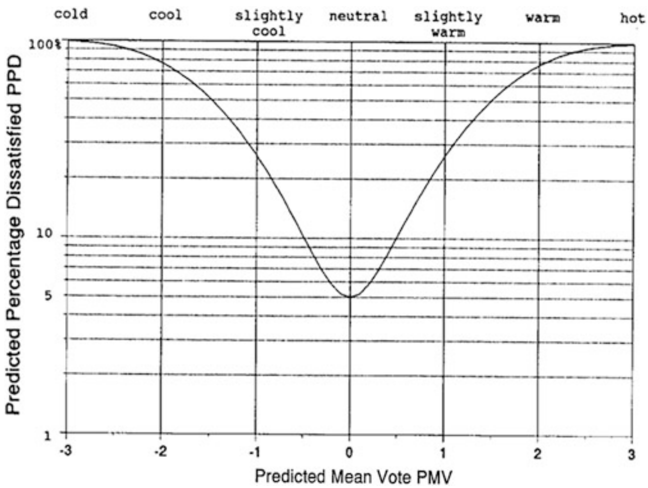


**Fig. 9.1** Relationship between the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD)

indicating where specific areas of the room require attention. Data to allow the determination of some PMV and PPD values are provided in Table 9.1.

**Table 9.1** Predicted mean vote (PMV) values from Fanger (1970)

Clothing insulation (Clo) (0, nude; 1.0, business suit; 2.0, heavy)

| $t_a = t_r$ | 0.1 | 0.3 | 0.5 | 0.8 | 1.0 | 1.5 | 2.0 |
|---|---|---|---|---|---|---|---|
| *Sitting relaxed.* $M = 1$ Met; $var = 0.1$ m s$^{-1}$ | | | | | | | |
| 10 | | | | | | –2.2 | –1.4 |
| 12 | | | | | | –1.8 | –1.0 |
| 14 | | | | | –2.5 | –1.4 | –0.7 |
| 16 | | | | –2.5 | –1.9 | –1.0 | –0.3 |
| 18 | | | | –1.9 | –1.4 | –0.5 | 0.0 |
| 20 | | | –2.3 | –1.3 | –0.9 | –0.1 | 0.4 |
| 22 | | –2.3 | –1.5 | –0.7 | –0.3 | 0.4 | 0.8 |
| 24 | –2.3 | –1.4 | –0.8 | –0.1 | 0.2 | 0.8 | 1.1 |
| 26 | –1.2 | –0.5 | 0.0 | 0.6 | 0.8 | 1.2 | 1.5 |
| 28 | –0.1 | 0.4 | 0.8 | 1.2 | 1.4 | 1.7 | 1.9 |
| 30 | 1.0 | 1.3 | 1.6 | 1.8 | 1.9 | 2.1 | 2.3 |
| 32 | 2.0 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.6 |
| *Sitting work or standing:* $M = 1.2$ Met; $var = 0.1$ m s$^{-1}$ | | | | | | | |
| 10 | | | | | –2.7 | –1.6 | –0.9 |
| 12 | | | | –2.8 | –2.2 | –1.2 | –0.6 |
| 14 | | | | –2.3 | –1.8 | –0.9 | –0.3 |
| 16 | | | –2.8 | –1.8 | –1.3 | –0.5 | 0.0 |
| 18 | | –2.9 | –2.1 | –1.2 | –0.8 | –0.1 | 0.3 |
| 20 | | –2.2 | –1.5 | –0.7 | –0.4 | 0.2 | 0.6 |
| 22 | –2.3 | –1.4 | –0.8 | –0.2 | 0.1 | 0.6 | 0.9 |
| 24 | –1.4 | –0.7 | –0.2 | 0.3 | 0.6 | 1.0 | 1.3 |
| 26 | –0.5 | 0.1 | 0.4 | 0.8 | 1.0 | 1.4 | 1.6 |
| 28 | 0.4 | 0.8 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 |
| 30 | 1.3 | 1.5 | 1.7 | 1.8 | 1.9 | 2.1 | 2.2 |
| 32 | 2.0 | 2.1 | 2.2 | 2.3 | 2.3 | 2.4 | 2.4 |
| *Standing light work.* $M = 1.6$ Met; $var = 0.1$ m s$^{-1}$ | | | | | | | |
| 10 | | | | –2.0 | –1.5 | –0.7 | –0.2 |
| 12 | | | –2.6 | –1.6 | –1.2 | –0.4 | 0.0 |
| 14 | | –2.9 | –2.1 | –1.3 | –0.9 | –0.2 | 0.3 |
| 16 | | –2.4 | –1.7 | –0.9 | –0.5 | 0.1 | 0.5 |
| 18 | –2.8 | –1.8 | –1.2 | –0.5 | –0.2 | 0.4 | 0.7 |
| 20 | –2.1 | –1.3 | –0.7 | –0.1 | 0.2 | 0.6 | 0.9 |
| 22 | –1.4 | –0.7 | –0.2 | 0.3 | 0.5 | 0.9 | 1.2 |
| 24 | –0.7 | –0.2 | 0.2 | 0.7 | 0.8 | 1.2 | 1.4 |
| 26 | 0.0 | 0.4 | 0.7 | 1.1 | 1.2 | 1.5 | 1.6 |
| 28 | 0.7 | 1.0 | 1.2 | 1.5 | 1.6 | 1.8 | 1.9 |
| 30 | 1.4 | 1.6 | 1.7 | 1.9 | 1.9 | 2.0 | 2.1 |
| 32 | 2.1 | 2.2 | 2.2 | 2.3 | 2.3 | 2.3 | 2.4 |

Assume rh = 50 %; still air; and no significant radiant source ($t_a = t_r$.) PMV: +3, hot; +2, slightly warm; +1, warm; 0, neutral; −1, slightly cool; −2, cool; −3, cold (*M* metabolic rate; *var* relative air velocity)

Instruments that measure air temperature, radiant temperature, humidity, and air velocity are specified in ISO 7726 (1998). Estimates of heat production due to activity are presented in ISO 8996 (2004). Estimates for the insulation of clothing are provided in ISO 9920 (2007). From the measurements and estimates, the PMV and PPD values can be calculated and an environment evaluated.

ISO 28802 (2012), provides a method of assessing thermal environments and includes the following subjective scales:

**Sensation scale:**

Please rate on the following scale how you feel now:
+3. Hot
+2. Warm
+1. Slightly warm
0. Neutral
−1. Slightly cool
−2. Cool
−3. Cold

**Uncomfortable scale:**

4. Very uncomfortable
3. Uncomfortable
2. Slightly uncomfortable
1. Not uncomfortable

**Stickiness scale:**

4. Very sticky
3. Sticky
2. Slightly sticky
1. Not sticky

**Preference scale:**

Please rate on the following scale how you would like to be now:
7. Much warmer
6. Warmer
5. Slightly warmer
4. No change
3. Slightly cooler
2. Cooler
1. Much cooler

**Draughtiness scale:**

4. Very draughty
3. Draughty
2. Slightly draughty
1. Not draughty

**Dryness scale**

4. Very dry
3. Dry
2. Slightly dry
1. Not dry

**Satisfaction scale**

Satisfied
Not satisfied

**Acceptability scale**

Acceptable
Not acceptable

The person conducting the survey should note the general impression of the thermal environment (e.g. hot, comfortable, cold, draughty etc.) and in particular local discomfort factors. Consideration should be given to the dynamics of how the room is heated up and cooled down, and how this will affect the occupants. Are there aspects of the occupant's behavior that can be identified with the influence of the thermal environment? What can the occupants do to avoid being too hot or too cold? (i.e. adaptive opportunity). Can they move around, adjust clothing, vary activity, close windows, adjust the thermostat, and so on. Risk assessment forms for thermal environments are provided in ISO 15265 (2004).

## 9.4 Indoor Acoustical Environments

Sound constitutes pressure changes in the air that are detected by the ear. The units of sound are therefore pressure ($Nm^{-2}$ or Pa). However, partly to reflect human response and also to reduce the range of values required to represent sound level (the ear can detect a very large range of pressures), a logarithmic scale is used where the actual sound pressure is divided by a standardized threshold value to provide the decibel scale (dB) where the sound level (SL) in decibels is given by Eq. 9.2:

$$\mathrm{SL} = 20 \log_{10}(P/Po) \tag{9.2}$$

Where: $P$ is the actual sound pressure level in the environment ($Nm^{-2}$), $Po$ is the standardized threshold sound pressure level ($2 \times 10^{-5}$ $Nm^{-2}$).

This sound level is often termed dB (lin) because it is a direct physical measure of sound pressure and does not take account of the nonlinear sensitivity of a person to sound frequency. Noise is defined as unwanted sound. And people are more sensitive to, and more annoyed by, some sound frequencies than others. The relative sensitivity of people to sound frequency is described by weighting curves; the most commonly used of which is the *A-weighting curve*. This curve is presented as the relative sensitivity of people to the frequency of sound at the same sound level. It is derived relative to the frequency to which the average person is most sensitive (1,000 Hz). It shows that for a given sound level, people are relatively less annoyed by sounds at lower frequencies. By weighting measured sound (noise) levels with the A-weighting curve, a dB (A) value is derived which is related to human responses of loudness and annoyance, and can be used to define optimum environments. In an office environment for example, keeping levels below 55 dB(A) would be desirable. More detail is given in Haslegrave (2005).

Sound level meters are used to measure noise and have built in 'filters' to provide automatic weighting of the sound signal. So dB (A) values are measured directly. IEC standard 61672-1 provides the specification of sound level meters for measuring A-weighted sound pressure level and equivalent continuous A-weighted sound pressure level. The ISO 9612 provides the method for determination of occupational noise exposure with sound level meters. The survey requires that the acoustical environment that people are exposed to is quantified. The sound level will have both spatial and temporal variation. A number of measures over different conditions will give a sound level profile (e.g. people in a room, equipment on or off etc.). Equivalent continuous A-weighted sound pressure level will give an overall average value of the sound levels over a longer period of time.

Subjective scales for acoustics typically use scales of annoyance specified in ISO/TS 15666 (2003). Generic terms such as preference, satisfaction, and acceptability can also be used.

Examples are:

**Annoyance scale:**

4. Very annoying
3. Annoying
2. Slightly annoying
1. Not annoying

**Preference scale**:

Please rate on the following scale how YOU would like it to be NOW:

4. Much quieter
3. Quieter
2. Slightly quieter
1. No change

**Acceptability scale**

Acceptable
Not acceptable

**Satisfaction scale**

Satisfied
Not satisfied

**Sources of noise**

Please indicate any sources of noise you can hear in your environment now.

The person conducting the survey should note the general impression of the acoustic environment, including background noise levels, and the general ability of the occupants to conduct any tasks. Particular noise sources such as machines, printers, footfall, people talking, ventilation fans, telephones etc., should be noted. Frequency and duration of noise may be noted for particular causes of annoyance, as well as intermittent or impulsive noise or pure tones that may lead to annoyance. The change of noise sources throughout the day should also be noted.

## 9.5 Indoor Visual Environments and Lighting

Indoor visual environments can provide pleasure as well as functionality in terms of lighting (daylight and artificial lighting) for effective visual performance. They can also provide discomfort due to glare or can cause distraction. A first stage in specifying optimum visual environments is to ensure that there is enough light. Light is the part of the electromagnetic spectrum that is detected by the eye. That is roughly wavelengths from 700 nm (red) to 400 nm (violet). Lighting levels vary greatly, from low levels indoors to very high levels outdoors in daylight. The eye cannot operate over the full range of levels to which it is exposed, so it 'adapts' to operate over a range of levels that it is experiencing at the time. The sensitivity of the eye to different wavelengths is described by the *V-Lambda* functions; one for *photopic* vision and daylight levels and one for *scotopic* vision and nighttime levels. In daylight, people are most sensitive to yellow light, but at night there is a shift in sensitivity toward green to which people are most sensitive. The units for light (*photometric*) take account of this relative sensitivity and instruments for measuring light are corrected accordingly.

Two important measures for specifying optimum conditions are the *illuminance level*, which is the amount of light arriving on a surface from all sources, and the avoidance of *glare*. Glare occurs when there are relatively bright areas in a visual scene and the eye has difficulty in adapting to an average level. This causes discomfort and loss in visual performance. Illuminance levels are measured in *Lux,* usually directly by a light meter. A level of horizontal illuminance at the workplace, say in an office, is recommended between 300 and 500 lux, depending upon how much detail is required in a task. Glare indices can be calculated from the relative intensity and direction of light sources in the visual field, but are often determined in assessment using subjective measures. Further details of visual and lighting environments are provided by Howarth (2005), Howarth and Bullimore (2005), and Boyce (2003).

CIE 69 standard provides the specification of an illuminance meter. Horizontal illuminance should be measured in a way that quantifies the level available in the visual scene of the person. It may also be appropriate to take specific task-related measurements. The level will vary with the location of people and objects between the lighting source and the surface. Where lighting levels vary, a number of readings may be necessary to quantify the lighting profile. Light levels can vary in space and time. They can be influenced by time of day, as outside conditions will often influence lighting levels. The person conducting the measurement should be careful not to interfere with the lighting levels received by the sensor. General guidance on the lighting of indoor workplaces can be found in ISO 8995 (2002). The ISO 28802 (2012) provides the following subjective scales for use in environmental surveys:

**Visual discomfort scale:**

Please rate on the following scale your visual discomfort now
4. Much discomfort
3. Discomfort
2. Slight discomfort
1. No discomfort

**Preference scale:**

Please rate on the following scale how you would like your visual environment to be now:
7. Much lighter
6. Lighter
5. Slightly lighter
4. No change
3. Slightly darker
2. Darker
1. Much darker

**Acceptability scale**

Acceptable
Not acceptable.

**Satisfaction scale**

Satisfied
Not satisfied

**Sources of glare**

Please indicate if you are experiencing any glare now.

The person conducting the survey should note the general impression of the visual environment, including background lighting levels and general ability of the occupants to conduct any tasks. Particular light sources that cause visual discomfort should be noted. The change of visual environment including light levels and sources throughout the day should be noted. A general impression of mood and esthetics can be recorded as this will relate to overall satisfaction. An impression should be taken as to whether the lighting and general visual environment is complementary to the purpose of the space; for example, does the general color or level of the lighting fit with the purpose of the space such as formal for an office or warm and intimate for a social space.

## 9.6 Indoor Air Quality

Indoor air quality can have a direct influence on health as well as an indirect influence on general well-being, comfort, and performance of tasks which can be related to productivity. (Wyon 2004). Direct effects on health can be caused by chemicals in the air, particulates including dust, gases, vapors, bacteria and viruses from exhalation and sneezing, and so on. They can interact with the skin, especially when sweating, or cause respiratory and other problems when breathed into the lungs. Limiting values for health are provided in ACGIH (2008) in terms of threshold limit values (TLVs). Some components that influence air quality are not perceived by people, but they can be dangerous. Appropriate instrumentation is needed to measure and monitor air quality and its effects on health.

As well as the avoidance of direct effects on health, it is important to design an environment that is stimulating and pleasant to work in, maybe with a feeling of freshness. The avoidance of smells, appropriate ventilation, and the introduction of fresh air will be important. Different ventilation systems affect air quality in different ways. In a normal mixed ventilation environment, although fresh air is introduced, people breath a mixture of air, some of which has been breathed before—by others. In displacement ventilation systems, where cool air is continuously fed to the floor and rises to extraction at the ceiling, there is not a mixture and pollutants are extracted; this requires careful design and implementation, however, and cool air on the floor with a temperature gradient (Hodder et al. 1998).

When people occupy an environment they breath in air, burn food in oxygen (from the air) within the body (to produce energy mainly as heat), and expire carbon dioxide ($CO_2$). In a sealed environment, or one where there is limited ventilation, there will be a build-up of $CO_2$ throughout a day. This can cause a change in behavior (e.g. in school children in classrooms), headaches, general feelings of irritation, lethargy, and sickness. In fresh outside air, levels of carbon dioxide are at 0.03 %. Expired air can be at around 4 % $CO_2$. Levels in rooms for example, of 1 % or more, will become unacceptable and clearly ventilation must keep levels well below that.

The build-up of $CO_2$ is not only a warning in itself, but can also be used as a surrogate to indicate the possible build-up of other contaminants and as an indicator of the effectiveness of ventilation systems. Measurement of $CO_2$ levels therefore, although not perfect, is often taken as an indication of air quality in general (ISO 28802 2012).

There have been attempts to produce indices of perception and satisfaction with air quality although none has been generally accepted. Of particular interest, is the work of Fanger (1988) who proposed the *olf* and the *decipol*. The olf is an index of the integrated intensity of all sources of 'smells' and is defined in terms of the equivalent to odors and smells given off by standard persons (1 olf is equivalent to the bioeffluents given off by a standard person; 2 olfs, 2 persons, and so on). The pollution this source of smells will cause is termed the decipol which takes account of the ventilation rate. The higher the ventilation rate the lower the pollution, the better the air quality, and the less dissatisfaction. Laboratory studies established olf values for different sources (e.g. people, stale carpets, new furniture, office equipment etc.) and dissatisfaction rates in terms of the decipol. A survey of an indoor environment then can identify percentage of dissatisfaction with the air quality using subjective methods. From that, the decipol value can be derived and if the ventilation rate is known, the olf value. It is important to note that in any survey of air quality that uses subjective methods, first impressions are important. Dissatisfaction ratings are determined by a panel of judges (experts or occupants) and they must give their first impressions of the air quality after coming into the indoor environment from an environment with fresh (outside) air. This is because people adapt to odors and smells. (Try entering a crowded room of people who have been in there for an hour or more. The occupants will not perceive the smells but the person who enters will). The effect of the smells will remain but perception will change with exposure time.

ISO 28802 (2012) recommends $CO_2$ as the physical measure used to assess the air quality in indoor environments. It is noted that there is no international standard for instruments to measure $CO_2$ although specification will be supplied by the manufacturer and the importance of calibration will apply. ISO 28802 (2012) also suggests subjective scales for use to assess air quality. Although these are not fully developed for this area, it is a useful starting point and they are presented below:

**Smelliness scale:**

4. Very smelly
3. Smelly
2. Slightly smelly
1. Not smelly

**Acceptability Scale**

Acceptable
Not Acceptable

**Satisfaction scale**

Satisfied
Not satisfied

**Sources of smells**

Please indicate any sources of smell in your environment now

The person conducting the survey should note the general impression of the air quality including any sources of smells. Inputs and outputs of air should be noted as well as circulation patterns, dead spots, and type of ventilation system. In buildings, inputs and exhaust systems should be identified for the whole building and particular attention paid to pollution sources. The change of air quality levels and sources throughout the day should be noted. Particular attention should be paid to the fact that people adapt to smells. It is important therefore to gain an impression when an occupant first enters a space as well as for prolonged exposure.

## 9.7 Indoor Vibration

Vibration is present in all indoor environments but with a major presence and effect on people in vehicles (land, sea, air, and space). Ride quality is of great importance and has clear effects on the health, comfort, and performance of people. In 'non-moving' indoor environments such as in buildings, vibration can be caused by outdoor activities such as road, rail, or aircraft traffic (or even blasting and construction work). It can also be caused indoors by refurbishment and repair work, or by people walking around (footfall), or machines, such as computers and printers in offices, and production machines in factories. Vibration is usually accompanied by noise and is not usually a dominant factor that influences the quality of most indoor environments. In buildings, any annoyance caused is often related to perception thresholds as any vibration, which is perceived, may be regarded as unacceptable. In extreme cases, damage and fear of collapse will be important. This may be from low frequency vibration in a high rise building (e.g. due to high winds) or due to high levels of higher frequency vibration caused by blasting operations for example. As with noise (and other environmental components) attitudes toward what the person thinks is the source of vibration will influence annoyance and other responses (e.g. earth tremors may lead to more severe consequences).

Level and frequency of vibration will be important as well as the direction it enters the body (horizontal, vertical etc.—Griffin et al. 1982; Griffin 1990). Frequency weighting curves are therefore used to provide weighted acceleration values that predict human response. Physical measures include acceleration in vertical, horizontal, and fore-and-aft directions with respect to a person, and sometimes also in roll, pitch, and yaw. ISO 8041 (2005) specifies the performance specifications and tolerance limits for instruments designed to measure vibration values for the purpose of assessing human response to vibration. ISO 2631 Part 1 (1997) provides general guidance on measurement, evaluation, and assessment of whole-body vibration and shock. For the evaluation of motion with respect to comfort, ISO 2631-1 recommends that the overall frequency-weighted root-mean-square acceleration or the vibration dose value is determined. ISO 28802 (2012) provides the following subjective scales for use in surveys:

**Uncomfortable scale**

6. Extremely uncomfortable
5. Very uncomfortable
4. Uncomfortable
3. Fairly uncomfortable
2. A little uncomfortable
1. Not uncomfortable

**Annoyance scale:**

4. Very annoying
3. Annoying
2. Slightly annoying
1. Not annoying

**Acceptability scale**

Acceptable
Not acceptable

**Satisfaction scale**

Satisfied
Not satisfied

**Sources of vibration**

Please indicate any sources of vibration in your environment now.

The person conducting the survey should observe how the motion is affecting a person's attention, behavior, and ability to carry out tasks. In a vehicle, motion will be expected but may interfere with driving or the ability to read or drink. In a building, vibration may be distracting or cause alarm or annoyance.

## 9.8 Other Environmental Factors and Specific Populations

The main components of the physical environment that influence human responses have previously been discussed. There are other factors that can be of influence, such as the tactile environment and the general esthetics of the environment. The general disposition of those experiencing the environment will also be influential. The person conducting an environmental survey should note the general atmosphere in the space in terms of social interaction. It is possible that complaints about the environment are fundamentally caused by general dissatisfaction at work. Management styles and worker relations are often influential. It is important when conducting a survey to take this into account. The person conducting the survey will become part of the social environment and may influence subjective responses.

Optimum environments will depend to some extent on the people who occupy the environment. People's response to the environment changes as they become older. Older people have a different sensitivity to the frequency of sound as well as to color, and there is a general deterioration in performance. People with physical disabilities vary in sensitivity to the environment depending upon the nature of the disability, any effects of medication, and any technical aids such as wheelchairs. Designing the environment so that people can adapt and optimize conditions to suit their requirements is generally important and a property of good environmental design. It is particularly important for 'people with special requirements' and can contribute to inclusive design. The ISO 28803 (2012) provides guidance and advice on environmental design for people with special requirements.

Differences between people across the world are not fully explored. However, it is by no means certain that requirements for Asian people for example, are identical to those for western people. In particular, how to design environments to take advantage of, and complement, different cultures has not been fully explored and offers exciting opportunities for environmental design in the future.

## 9.9 Sustainable Comfort, Adaptive Opportunity, and Energy

It is important to recognize when designing an environment or conducting a practical survey, that people will behave in a way which will avoid discomfort or dissatisfaction. In using an observation assessment form, where the person conducting the survey will make general observations concerning the environment, it is useful to identify the opportunity people have to do this (Appendix 1). This will be determined by the organizational and social environment as well as the environmental design. An environment where people can move around, adjust clothing, and/or have the ability to change environmental conditions (thermostat, light levels, open a window etc.), may be more satisfactory than one where people have restricted opportunity. This can be caused by the task (e.g. emergency telephone operator who cannot leave the workplace), the organization (e.g. strict dress code to wear a uniform), or the building (e.g. sealed windows) for example. It can also be caused by the characteristics of the person (e.g. people with disabilities with restricted movement). In any environmental design or survey, such adaptive opportunities should be considered. Designing for sustainable comfort meets not only the requirements for good environmental design, for which there are many combinations of environmental variables and methods, but also takes account of the resources used to achieve the requirements. Some designs are more sustainable than others in terms of the use of resources such as energy. If a design can include adaptive opportunity, it will be possible to achieve comfort not only to take account of individual requirements, but also with a more efficient use of resources. Parsons (2012) has made the first attempt to consider adaptive opportunities in the context of total environments, sustainable comfort, and energy. A summary is provided in Table 9.2.

**Table 9.2** Sustainable environmental comfort and adaptive opportunity (Parsons 2012)

| Environment | Example of Parameters | Adaptive opportunity | Contribution to sustainability | Comment |
|---|---|---|---|---|
| Thermal | Air temperature<br>Radiant temperature<br>Humidity<br>Air velocity<br>Metabolic rate<br>Clothing insulation | Vary combinations of important parameters to optimize energy use. In the heat, adjust posture to maximize surface area exposed to air. Move out of the sun. Reduce clothing to minimum acceptable level. Avoid work or activity in the hot part of the day. Go to a cooler place, turn on fans, open windows. In the cold, add clothing to acceptable maximum levels. Increase activity where possible. Reduce surface area exposed to air by curling up and changing posture | Wider range of conditions available provides greater opportunity to select low energy demand designs | Area has been investigated and well understood. Need to link more with actual energy savings |
| Acoustical | DB(A)<br>DB(A) Leq | Move away from noise. Adjust noise at source in terms of both amplitude and frequency. Use ear plugs or muffs where appropriate | Energy related but specific model not clear | Need more research into the use of adaptive models in this area |
| Visual and lighting | Horizontal illuminance | Move around to avoid lighting areas that do not need lighting. Adjust behavior so that lights switch off when not needed | Considerable direct savings in time lights are on | More research needed in identifying human behaviors and in energy demand management systems |

(continued)

**Table 9.2** (continued)

| Environment | Example of Parameters | Adaptive opportunity | Contribution to sustainability | Comment |
|---|---|---|---|---|
| Air Quality | $CO_2$ levels | Move away from smells. Open windows where appropriate | Opening windows can reduce energy required for ventilation, interaction of air quality, and temperature. So some advantage may be gained at lower temperatures for comfort | More research needed in energy, cost of providing mechanical ventilation, and possible benefits of using alternative methods |
| Vibration | Acceleration in vertical, horizontal, and fore-and aft directions with respect to a person. Sometimes also roll, pitch, and yaw. Frequency-weighted rms or vibration dose value | Move away. Mostly unwanted; so optimum is absence of vibration in many cases. Changing posture will help to tolerate in some cases | More efficient design of machines will reduce vibration and energy waste | Vibration is generally an unwanted environmental component and its reduction is usually associated with less energy required for a more efficient machine |

## 9.10 Conclusion

Possessing the ability to quantify human responses to indoor environments is essential for the development and continued improvement of internal spaces in buildings. Using the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), it is possible to gage such responses; and together with the equipment to measure physical indoor variables, engineers have the required data to assess the dual impact between occupant and building. Provision of ISO standards (International Organization for Standardization) facilitates a uniform approach for measurement, appraisal, and implementation of indoor environmental design. Environmental components such as: thermal comfort, acoustics, visuals and lighting, air quality, vibration, and other social related factors can be rigorously assessed through established methodologies. Further work is necessary to address differences in occupant culture, nationality, age, and attitude to enrich our understanding of how people respond to indoor environments, monotonically and within multiple-occupied zones. Not least, industry professionals and academics are striving to better understand occupant response to environments in the context of sustainability from a holistic perspective. Lastly, as we move toward a low carbon built environment, and while climate produces weather extremes, buildings play an increasingly important role and indoor design must evolve to ensure occupants have sufficient adaptive opportunities to secure comfortable and healthy places in which to live.

## A.1 Physical environment and human performance assessment form

Complete this assessment form in the context of the organizational culture and mission, the job requirements of the staff, and how the physical environment may affect their performance and productivity

| Category | Comments |
|---|---|
| *General impression* (One sentence and one word descriptors) | |
| *Good points* (include what the best aspect is) | |
| *Bad points* (include what the worst aspect is) | |
| *Air Quality* (immediate impression on entering - stuffy, smelly, and dusty?) | |
| *Thermal Environment* (hot, cold, humid, draughty, hot/cold surfaces, and sweaty) | |
| *Lighting and visual environment* (easy to see, lighting levels, clean windows and lights, glare, and general appearance) | |
| *Noise and vibration* (detect vibration, footfall, background noise level, interruptions, interference with task, annoying, noise sources, and echoes) | |
| *Furniture* (appearance and condition, fit for purpose, fit to person's size, telephone, and chair) | |

(continued)

(continued)

| Category | Comments |
|---|---|
| *Computer equipment* (correctly positioned and adjusted, glare on screen, reflections, and orientation) | |
| *Overall layout* (storage space, organization of work, filing system, coats, and accessories) | |
| *Adaptive opportunity* (clothing adjustment, move around, open window, control over conditions, level of activity, and take breaks) | |
| *Distraction* (sources of distraction from task that cease work or interfere with performance) | |
| *Overall conclusion*: Environment optimum for performance? | Yes or No |
| *Recommendations*: | |

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# Chapter 10
# Energy Efficient Building Design

**Runming Yao and Alan Short**

**Abstract** This chapter covers the basic concepts of passive building design and its relevant strategies, including passive solar heating, shading, natural ventilation, daylighting, and thermal mass. In environments with high seasonal peak temperatures and/or humidity (e.g. cities in temperate regions experiencing the Urban Heat Island effect), wholly passive measures may need to be supplemented with low and zero carbon technologies (LZCs). The chapter also includes three case studies: one residential, one demonstrational, and one academic facility (that includes an innovative passive downdraft cooling (PDC) strategy) to illustrate a selection of passive measures. *Learning Outcome*: On successful completion of this chapter, readers will be able to: (1) summarize the physical processes underpinning the energy (thermal) balance in buildings; (2) fully grasp the key concepts governing passive architecture/design; (3) understand how efficient design contributes to energy and carbon reduction; (4) comprehend how simulation tools can aid the design process; (5) identify different ventilation strategies used in; and (6) observe how energy efficient design benefits actual buildings through different case studies.s

**Keywords** Building envelope · Downdraft · Natural ventilation · Passive design · Passive solar · Thermal mass

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## 10.1 Introduction

Architectural principles and building services design can significantly influence operational energy consumption. There are many approaches to 'maximizing energy efficiency' while 'reducing a building's energy demand'; there being a subtle difference between the two concepts. *Passive design*, also known as 'bio-climatic design', helps maximize occupants' comfort and health, by harmonizing local climatic and site conditions with architectural design. Such an approach uses building facades and calculated positioning of glazing to control, store, and circulate solar energy which beneficially influences heat, air movement, and daylight, avoiding the use of mechanical plants to minimize energy consumption. Good passive design can undoubtedly minimize building services requirements through the consequent reductions in heating, cooling, and artificial lighting loads. Successful building design is also sensitive to the environment and responds to climate and dynamic factors such as diurnal and seasonal weather fluctuation, together with occupancy pattern and density.

## 10.2 Climate

Climate is regarded as weather averaged over a long period. The standard average period is 30 years, as recommended by the World Meteorological Organisation (Wong and Chen 2009). The classification of world climates is dependent on various climate parameters such as temperature, humidity, and precipitation. Climate should be considered as one of the most important factors in building and system design, as it has considerable impact on energy use. However, globalized building typologies and envelope types tend to ignore or fight against regional climate characteristics, not least in the popularity of 'all-glass' envelopes. Building design should 'adapt' to known and historic climatic characteristics to achieve local and regional comfort expectations to minimize energy use, rather than be sealed to exclude climate. Local populations adapt to their prevailing climate. Worldwide adaptive thermal comfort study reveals significant adaptation to temperature in particular, so that peak acceptable temperatures worldwide vary quite significantly (Humphreys 1978; Brager et al. 1998; de Dear and Brager 1998; Yao et al. 2009). Industry practice recognizes six particular climatic zones in building design, characterized as: hot humid, hot dry, warm humid, warm dry, temperate, and cool.

## 10.3 Strategic Design

It is increasingly recognized that, ultimately, a building's performance is largely determined by its 'strategic' design as considered within the earliest stages of a project. For example, decisions about plan depth, orientation, and fenestration (the glazing scheme) are all key strategic elements of the design, which influence the potential for daylight and natural ventilation, which in turn determine the demand for heating and cooling. These early design decisions have inevitable knock-on effects for plant and equipment, which have a major impact on building energy performance. Building design is an iterative process, often requiring the design team to rethink fundamental aspects. An integrated building design strategy should be considered at the earliest design stage or the exercise will become one of remedial design intervention to correct a flawed design retrospectively.

At the strategic design stage, the issues concerning the interrelationship between architecture and engineering should be addressed, while confirming their respective contribution to the energy efficiency of the building. Informed decisions which affect the holistic concept of the building need to be taken during this stage, so that members of the design team can proceed with detailed design work, fully aware of the relationship between the components and the building as a whole. Resources must be made available to help inform those in the decision-making process, who determine the fundamental strategies.

## 10.4 Energy Consumption in Buildings

Estimating energy consumption for space heating (SH) and space cooling (SC) in buildings, involves calculation of associated heat gains and losses. When a room's heat losses are greater than its heat gains, mechanical heating is required; whereas if heat gains are greater, cooling is required to maintain indoor thermal comfort. Figure 10.1 illustrates heat gains and losses within a room. A key principle of passive design is to: prevent heat loss in winter (by insulation and the maximizing of solar gain); and reduce heat gains in summer (particularly by minimizing solar gains). The resulting combination reduces heating and cooling loads.

*Heat Gains*

- Solar gain—heat directly transmitted to the indoor environment through glazing and heat absorbed by opaque elements (e.g. walls), which is conducted indoors;
- Conductive gain—heat gains conducted through opaque wall, roof, and glazing elements due to higher external air temperature;
- Casual gain—heat emitted from occupants, appliances, office equipment, etc., within the room;
- Artificial lighting gain—heat emitted from luminaries (light fittings);
- Auxiliary heating—heat contributed by actual heating systems, including accidental gains from their transmission (i.e. poorly lagged pipes).

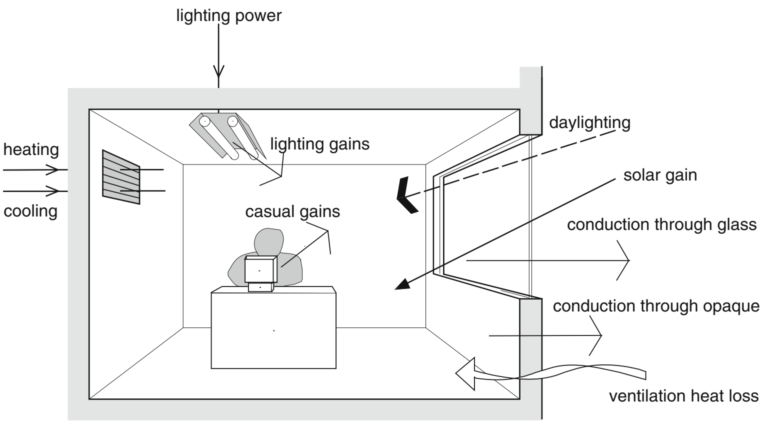


**Fig. 10.1** Heat gains and heat losses within a room (*Source* Baker and Steemers 1995)

*Heat Losses*

- Conductive loss—heat loss conducted to the exterior environment through the building's opaque elements and glazing, due to higher internal air temperature;
- Ventilation heat loss—heat lost through open windows, trickle vents, and other controllable openings;
- Infiltration heat loss—heat lost through openings to the exterior via gaps, cracks, holes, and vents.

The overall *heat loss* (H) (in Watts) from a building can be calculated using Eq. 10.1:

$$H = H_{\mathrm{t}} + H_{\mathrm{v}} + H_{\mathrm{i}} \tag{10.1}$$

where: $H$ = overall heat loss, $H_{\mathrm{t}}$ = heat loss due to transmission through walls, windows, doors, and floors, $H_{\mathrm{v}}$ = heat loss caused by ventilation, $H_{\mathrm{i}}$ = heat loss caused by infiltration (all units in Watts).

## 10.5 The Concept of Passive Design

A true passive building design, that is, a truly net-zero-energy building, uses its physical architectural configuration and its materials. It is constructed to provide the necessary insulation, daylighting, heat, and coolness within a building, without the use of mechanical and electrical equipments. Passive design requires very careful consideration of the local climate, solar energy, and wind resource. It will have a fundamental effect on the resulting architecture. A *Net-Zero-Energy* building could be argued to fall short of this ideal; it expends energy to sustain itself but attempts to deliver this energy requirement through renewable sources on- or off-site. The principal elements available to deliver passive design include: optimized building orientation, appropriate window sizing and placement, window shading devices where necessary (to reduce summer heat gain and ensure winter heat gain), and the proper sizing of thermal energy-storage mass. These elements tend to conflict. A good passive design involves brokering all of the influencing factors into an optimized whole.

Heat is distributed primarily by natural convection and radiation, although low-wattage fans may also be used to circulate room air or maintain necessary ventilation. Passive design encourages the application of *natural ventilation* to cool a building, and *passive solar* strategies to warm and light it. However, modern nondomestic buildings may need to shed heat throughout the year. Good passive design can minimize the need for building services due to reduced heating, cooling, and lighting loads. Where appropriate, designs should avoid simply excluding the environment but should respond to dynamic factors such as diurnal and seasonal weather fluctuations and occupancy patterns. The *LT Method* (Lighting and Thermal) (Baker and Steemers 1995; Baker and Yao 2002) for example, gives useful and rapid insight into the potential for passive design. This method will be introduced later in Sect. 10.6.

*Building Orientation*

Orientation (north, south, etc.) is fundamental to a building's overall environmental performance in terms of summer heat gains and winter heat losses. Air conditioning can be minimized or avoided altogether, or required at above the prevailing rate for the building type if the orientation is inappropriate. For example, north-facing windows (in the northern hemisphere beyond the tropic) experience very little solar gain and benefits are often gained by having the major building axis pointing east/west. East- or west-facing glazing is more difficult to shade from direct sunlight, particularly from the southwest, as solar angles are low in the early afternoon when solar radiation is still high. South facades receive both direct and diffuse radiation and are relatively more straightforward to control.

*Built Form*

The building envelope, which separates indoor and outdoor environments, should be considered as a climate modifier, rather than solely as a means of excluding external climatic conditions. In addition to providing structural support and finish, the envelope generally has four main functions:

- In cold weather: to reduce heat loss through the fabric to maximize the benefits of solar and internal heat gains, and reduce losses associated with uncontrolled air infiltration;
- In warm weather: to minimize solar heat gains to help avoid overheating; possible use of solar shading devices near windows; appropriate use of thermal mass to attenuate heat gains;

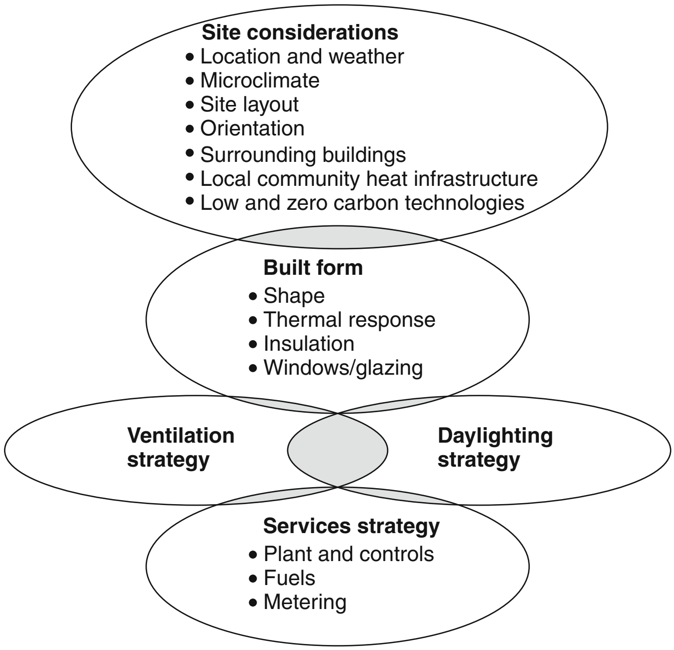


**Fig. 10.2** Sketch design process (adapted from CIBSE Guide F by permission from CIBSE)

- To achieve the optimum natural ventilation level;
- To optimize daylighting.

*Site Management*

Site layout, building scale, and available fuel source present both opportunities and constraints. Site conditions can influence key decisions regarding built form (building shape and geometry) and can be advantageous when promoting passive ventilation and daylight strategies. The sketch design process is shown in Fig. 10.2 (CIBSE 1998).

*Insulation*

Thermal transmittance or overall U-value (W/m$^2$K) of the building envelope is the principal factor in the determination of the steady-state heat loss/gain. Reducing the thermal transmittance of the building envelope, by increasing its insulation level, can help reduce heating demand, resulting in lower heating energy consumption. Increased insulation within a building can also reduce the required capacity of its heating system and simplify its design and operation.

Adequate insulation should feature early on in ‘good’ initial design schemes, not least in the emerging budget. However, insulation can also be added to existing buildings retrospectively. Case studies show that the additional low cost of insulating materials can be easily offset by savings from the smaller heating plant

**Table 10.1** Specific heat for common building materials (*Source* Baker and Steemers)

| Material | Heat capacity KJ/m³ °C | Specific heat KJ/kg °C |
|---|---|---|
| Exp. polystyrene | 25 | 1.00 |
| Fibreboard | 300 | 1.00 |
| Softwood | 730 | 1.20 |
| Hardwood | 900 | 1.23 |
| Gypsum plaster | 1050 | 1.10 |
| Lightweight concrete | 1000 | 1.00 |
| Brick | 1360 | 0.80 |
| Dense concrete | 1760 | 0.84 |
| Water | 4200 | 4.20 |

required and annual energy savings in fuel consumption. Subsequent fuel savings continue throughout the operational lifetime of the building. Another key benefit achieved from good thermal insulation is the reduced risk of surface condensation due to warmer internal surfaces.

Good thermal insulation also reduces heat flow into a building, when external temperature is greater than internal temperature. In other words, a well-insulated structure will, if ventilation is controlled, stay cooler in the summer than a poorly insulated structure. Buildings in hot climates actually require insulation, which may seem counterintuitive.

*Thermal Mass*

Thermal mass can be defined as: *'the material of the building which absorbs or releases heat from or to the interior space'*. The materials concerned are usually part of the structure or envelope, and are typically dense materials such as concrete, brick, or stone. *Specific heat*, that is, *'the heat energy required to raise a kilogram of a given material by* 1 °C*'*, can be used to describe the ability of material to store heat (Baker and Steemers 1995). Table 10.1 lists values for common building materials.

Night cooling in conjunction with thermal mass, typically a heavy concrete structure, can be used as a means of avoiding or minimizing mechanical cooling demand in a nondomestic building. During the summer months, ambient air that is circulated through a building through the night, absorbs and removes heat thereby cooling the building fabric. The cooler 'starting' temperature of the building fabric the following morning is then available to absorb heat during the day, offsetting heat gains, thereby reducing or eliminating the need for mechanical cooling in order to maintain thermal comfort. In cases where heavyweight structures can benefit from significant night ventilation, window operation should be assumed to be automated, prior to consultation with building occupants and facilities managers who may feel the more complex controls regime to be a burden on future occupants. Effective automation requires complete integration with other control systems and should provide management with feedback. This can be exceptionally challenging for the local construction industry, thus correct commissioning procedures are vital (Short et al. 2009).

**Table 10.2** Envelope air leakage rates recommended by CIBSE—AM10 guide TM23 (CIBSE 1997, 2000)

| Building type | Air leakage index | Permeability $(m^3/h)/m^2$@50 pa |
|---|---|---|
| Natural ventilation | 10.0 | 7.0 |
| Low energy/air-conditioned | 5.0 | 3.5 |

Cellular buildings that have many partitioned zones often have a high thermal mass, regardless of material choice. This is because of the increased surface area resulting from a greater number of rooms, which increases thermal response. This can balance the effect of poor cross-ventilation, but effective night ventilation is still necessary. However, interior design schemes can inadvertently reduce available thermal mass by covering exposed slabs and walls with lightweight linings, altering their thermal absorption property. The management of the building must be aware of these physical principles when design briefs are initially created for interior design contractors or future refurbishments. Thin 'phase-change' materials could present a solution to this problem in the near future, offering the effect of phase changes in the lining material in step with rising and falling internal temperatures, releasing coolness as temperatures rise and vice versa.

Heavyweight buildings can include spaces which actually perform as lightweight buildings; for example, large glazed entrance halls. Such areas can receive excessive solar gain and be subjected to higher heat losses than other areas within the building. This often necessitates the need for independent zone controls which command a fast response, adapting to frequently changing internal conditions.

*Air tightness*

Air tightness is a measure of how a building performs in allowing *unwanted* air movement through the building envelope, known as *air leakage*. More specifically, air leakage can be defined as: *'air movement to and from a building which is not for the specific and planned purposes of exhausting stale air or drawing in fresh air'*. Buildings can be tested for air leakage using a pressure test. This entails a large cylindrical trailer-mounted fan blowing air into a building at a pressure of 50 Pa, with all doors and windows closed, enabling on-site equipment to calculate an 'air changes per hour' value.

Air leakage should never be classified as natural ventilation. Likewise, it cannot be controlled or cleaned/filtered, and will not provide adequate or evenly distributed ventilation. Ventilation strategies should never rely on air leakage values, but should provide purposely designed systems based on the assumption that the envelope will be 'relatively' airtight.

The building fabric should be as airtight as possible, determined by design, and most importantly, build quality, to take advantage of a well-designed ventilation strategy. 'Build tight, ventilate right' is the industry expression: true for both mechanical and naturally ventilated buildings. Table 10.2 lists the envelope air leakage rates recommended by the Chartered Institution of Building Services Engineers (CIBSE) (guide TM23).

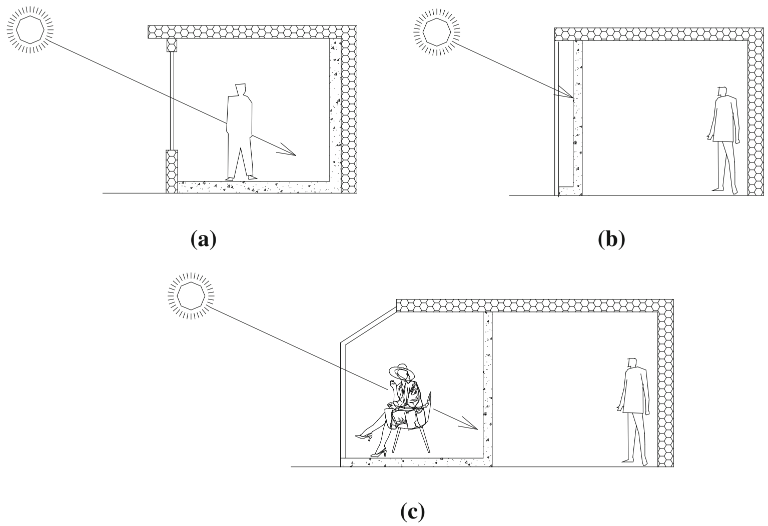

Fig. 10.3 The three main types of passive solar space heating systems

*Passive Solar*

'Passive solar' refers to a concept that collects, stores, and redistributes solar energy around a building without use of fans, pumps, or complex controllers. Its functionality relies on an integrated approach to building design, where basic elements such as windows, walls, and floors play a multifunctional role. For example, walls not only support roofs and provide shelter, but also act as heat storage and behave as heat-radiating elements. Using this approach, the various building components simultaneously satisfy architectural, structural, and energy requirements. Passive solar heating systems require two key elements: a *collector*, typically consisting of south-facing glazing; and an *energy-storage* element which usually consists of rock or water, providing thermal mass. Depending on the relationship between these two elements, there are several possible types of passive solar systems which are applicable. Figure 10.3 illustrates the three main concepts: (a) it lets the shortwave solar energy enter but blocks the heat from escaping; (b) the thermal mass inside the building then absorbs this heat both to prevent daytime overheating and to store it for nighttime use; and (c) the proper ratio of mass to south-facing glazing.

*Light and Shading*

Glazing, commonly in the form of windows, is an essential building element when considering sustainability. In low-energy building design, glazing systems should consider daylighting and shading simultaneously. Designers should maximize daylight in order to reduce artificial lighting demand, while maximizing solar energy contribution for winter heating. Conversely, demonstrating design challenges, designers should minimize solar gains during summer in order to reduce space heating and cooling demand. In addition, shading devices such as blinds can reduce glare from windows and provide privacy.

Daylight normally penetrates about 4–6 m from the window into the room. Adequate daylight levels can be achieved up to a depth of about 2.5 times the window head height. Where single-sided daylighting is proposed, the following formula gives a limiting depth (L) to the room:

$$(L/W) + (L/H) < = 2(1 - \text{ Rb}) \tag{10.2}$$

where: $L$ = room depth in meters, $W$ = room width in meters, $H$ = height to top of window in meters, Rb = the average reflectance of internal surfaces.

In nondomestic buildings, the window area should be about 20 % of the floor area to provide sufficient light to a depth of about 1.5 times the height of the room.

*Natural Ventilation*

Naturally ventilated (NV) buildings do not use mechanical systems to move air around a building. Moreover, natural ventilation has a dual purpose: to provide occupants with fresh air, which reduces occurrences of *Sick Building Syndrome* (SBS) for instance, and for cooling (when weather conditions are suitable). Defining the optimum ventilation rate (liters per person per second) is crucial to energy efficiency. Insufficient fresh air compromises internal air quality: too much air results in excessive energy consumption.

There are different types of natural ventilation strategies depending on building form and room layout, these include:

*Single-Sided Ventilation*

Single-sided ventilation relies on opening(s), typically windows, situated on only one side of a room or enclosure. This situation commonly occurs in cellular buildings where some rooms only have one external wall with windows on, and internal doors on the other side(s). Stack-induced airflow increases with a greater vertical window separation, and with increasing difference between internal and external temperatures. To maximize the vertical distance over which the stack pressures behave in a room, it is sometimes necessary to position ventilation openings independently, above and below windows. Low-level inlets must be sited with care because they could create low-level draughts in cold weather. As well as enhancing ventilation rates, doubling the quantity of openings also increases penetration of fresh air into a space.

*Cross-Ventilation*

Intuitively, cross-ventilation occurs where there are openings (windows or vents) on two or more different sides of a room or enclosure. For instance, air flows from one side of the building to the other, entering through one window and leaving through another, on the opposite side of a room. Cross-ventilation is usually wind driven. As cooler air moves into and across an occupied space, it absorbs heat and encourages the removal of pollutant molecules. Consequently, there is a limit on the depth of space which can be effectively cross-ventilated. This limitation constrains plan depth, often leading to narrow plan depth buildings. Modest floor areas due to narrow plan depths are usually compensated for by including a full height atrium or courtyard in the center of a larger building. The narrow plan depths associated with this approach have the added benefit of enhancing the potential for natural lighting.

The principle design challenge associated with cross-ventilation strategies is to create a building form that will ensure a significant difference of wind pressure coefficient between the air inlet and outlet openings. This task is even more complex for buildings with courtyards because the air in the courtyard itself and immediately at the leeward side of the building (downwind) will be at similar pressures.

Another challenge in ensuring effective airflow is 'resistance'. For example, insufficient airflow, particularly in summer when gentle breezes prevail, occurs when windows on one side of the building are closed, or if internal partitions (particularly full height ones) restrict the flow of air across the space. In such situations, the ventilation mechanism is effectively single sided.

*Stack Ventilation*

Stack ventilation is used to describe strategies which use the force of buoyancy to drive air movement. Buoyancy magnitude is determined by the difference in internal and external air density, which is a function of air temperature and moisture. Warmer air rises and leaves the building, typically through openings near the top, and 'new' fresh air is drawn into the building, generally through low-level openings near the ground. The 'drawing in' of new air occurs due to physical principles of displacement. The effectiveness of stack ventilation can be enhanced by designing the stack outlet located in a region of wind-induced negative pressure. Subsequently, this requires attention when designing the position and shape of the stack outlet.

By its nature, stack ventilation encourages air movement in the same manner as cross-ventilation: air enters one side of a space, and leaves from the opposite side. Air flows across the entire width of a building, entering at low level and exhausted via a chimney. Equally, cross-ventilation airflow enters through openings at low level and is drawn across the room space up into a central chimney-like structure, such as an atrium, from where it exits at high level.

Stack and cross-ventilation can be effective across a room width of five times the floor to ceiling height, from the perimeter (inlet) to where the air is exhausted, to the stack in stack ventilation cases.

*Chimney Ventilation*

A chimney provides a means of generating stack ventilation. If the chimney has a large surface area exposed to the weather, it needs to be well insulated.

Chimneys provide no functional purpose other than ventilation. Consequently, they are simply sized to satisfy the pressure drop requirements. They can be in the form of a single linear chimney or several smaller chimneys distributed around the building to suit the required ventilation flow path. For example, if the building faces a busy road, it would be possible to place the chimneys on the roadside.

A 'solar' chimney, in which glazed elements are incorporated into the chimney structure, can enhance stack pressures. Solar radiation enters the chimney through the glazing and air is captured by absorbing surfaces. Heat is then released to the air by convection, promoting buoyancy. Care has to be taken to ensure that there is a net heat gain into the chimney during cooler weather (i.e. the solar gain must be greater than the conduction loss). If this balance is not achieved, buoyancy is reduced and the chimney is less effective. In cold weather, conduction heat loss results in the glass having a low surface temperature; this may be sufficient to generate downdrafts, inhibiting the general upward flow through the chimney.

Another important design aspect is the detail of the chimney outlet, which should be located in a negative wind pressure zone. This negative pressure zone can be created by careful design of the roof profile and/or the chimney outlet. If the outlet is not properly designed, the wind scoop can create positive pressure and completely disrupts the upward flow.

*Atrium Ventilation*

An atrium is a variant of the chimney ventilation principle. In fact, the same effect could be achieved with a central column of chimneys. The essential difference is that the atrium serves many more functions than the chimney; for example, it provides space for circulation and social interaction. As it may provide an attractive usable space, the location of the atrium is a key component in the organizational planning of the building. Thus, other criteria may restrict the flexibility to locate the atrium to maximum advantage for ventilation.

Atria provide one significant ventilation advantage: the air can be drawn from both sides of the building toward a central extraction point, thereby doubling the width of the building that can be ventilated effectively by natural means. The atrium also provides the opportunity for daylight penetrating into the center of a deep plan building; it also provides attractive usable space, often housing plants. Atria can assume various forms, but for natural ventilation to work effectively, the maximum distance from building perimeter to atrium must conform to cross-ventilation limits earlier discussed (i.e. about 15 m). If the atrium can provide good daylighting to the adjoining space, the majority of this 15 m span can be predominantly day lit for much of the time, thereby providing both an energy and environmental benefit. The atrium can also act as a buffer space to reduce winter conduction losses from the surrounding accommodation. However, top blinds and stack ventilation should be considered in design in order to prevent overheating in summer.

*Double Façade Ventilation*

The double façade is a special form of solar chimney. The absorbing façade surfaces need to promote convective flow and the space between the façade skins often includes cavity blinds which prevent direct solar gain passing through the inner facade to occupied space.

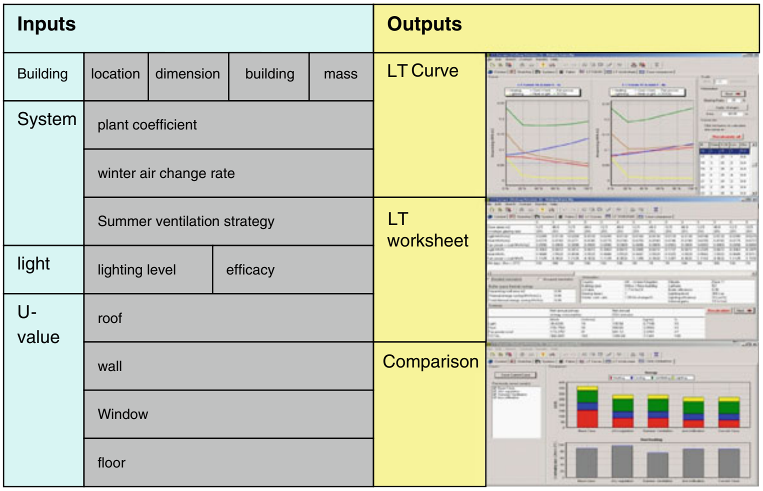


**Fig. 10.4** LT Europe software: input and outputs LT Curves

One approach is to use the cavity as a supply plenum rather than an extract plenum. Outside air is introduced into the cavity at low level; the cavity then acts as a solar collector, preheating the fresh air. The warmed air is then supplied to the occupied zones through ventilation openings between the cavity and the space. If the air in the cavity is too warm, it can be exhausted outside or to a heat recovery device. Local and national fire and smoke legislation may constrain the scope of double facades through compartmentation at floor levels.

Material selection for the double façades is very important. The efficiency of the solar collector can be significantly reduced if conduction losses are too high. Condensation risk should also be assessed, taking into account the temperature and relative humidity of the air entering the cavity, and the temperature of the glass.

## 10.6 Strategic Design Tool: LT Method

The *LT method* (Baker and Steemers 1995; Baker and Yao 2002) is an integrated energy design tool dedicated to the basic energy modeling of buildings, used at the very early design stages. The software features a European climate database and is commonly used for European projects; now extended to include some cities in China. Designers enjoy an intuitive interface that allows them to propose various design options in a timely fashion, while being provided with a good indication of energy consumption. Figure 10.4 illustrates the various software inputs and associated outputs.

A set of LT energy performance curves for heating, cooling, ventilation, and lighting, is shown in Fig. 10.5. The curves, which are a component of the software output, show energy use as a function of the glazing ratio in two passive zones of

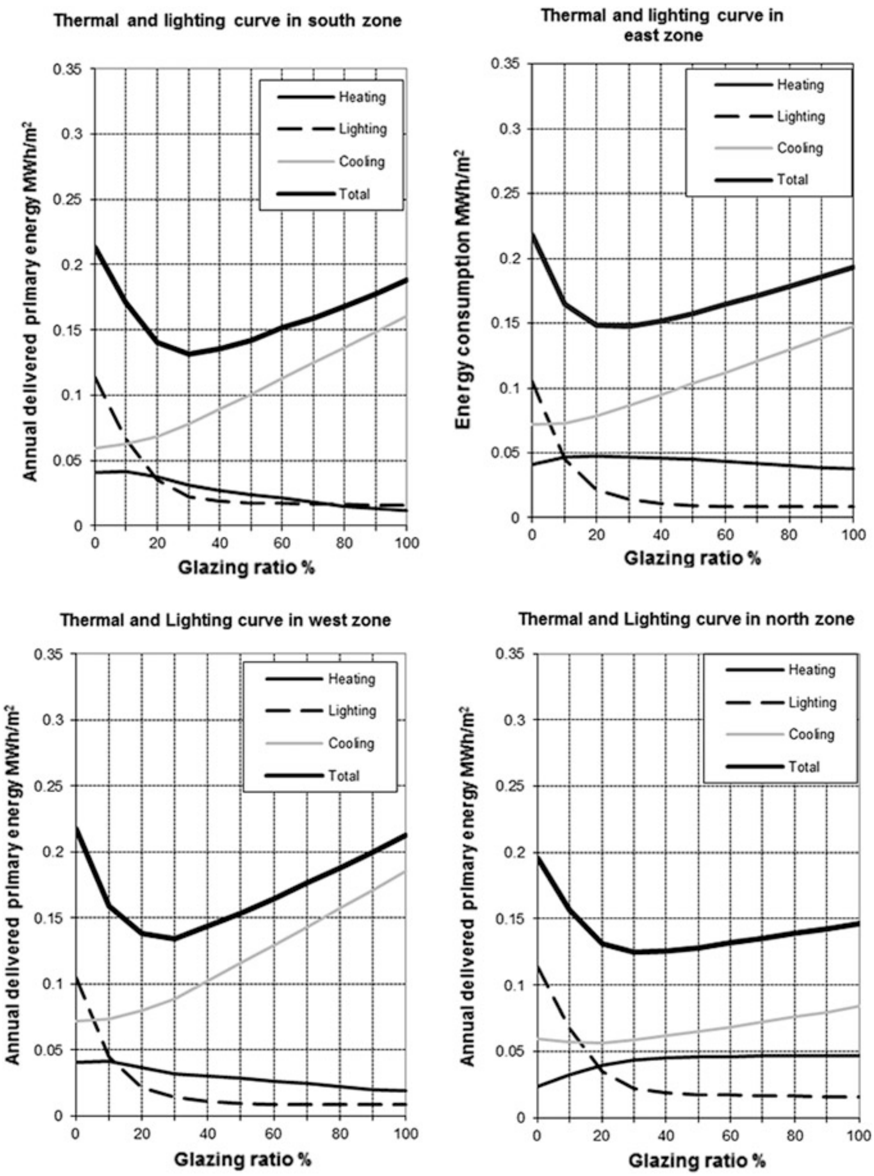


**Fig. 10.5** LT curves showing annual energy consumption per square meter for heating, cooling, ventilation and lighting, and overheating days, as a function of glazing ratio

an office building in Beijing. Such analysis can facilitate quick comparisons with relative ease.

It can be seen from the curves that cooling loads rise inexorably as the glazing ratio increases, even behind a north elevation.

**Fig. 10.6** View of the BedZED development (Image: Lin Hao)

**Fig. 10.7** Thick external wall with super insulation (Image: Lin Hao)

## 10.7 Case Study Examples

### *10.7.1 BedZED-Beddington, UK*

Located in the London Borough of Sutton, *BedZED* is developed through a partnership between *BioRegional Development Group*, *Bill Dunster Architects*, the *Peabody Trust*, *Arup* and the cost consultants *Gardiner and Theobald*. Designed as a prototype 'eco-village', BedZED was completed in 2002 and includes 82 residential homes and 18 live/work units (Fig. 10.6).

*Energy Conservation Features*

Heat loss is drastically reduced by superinsulation to the roofs, walls, and floors, so that heat gain from sunshine, lights, appliances, hot water, and everyday activities such as cooking, keep the houses comfortably warm in winter. (The thick walls of

**Fig. 10.8** Rooftop wind cowls (Image: Runming Yao)

**Fig. 10.9** Indoor air outlet fixed in the kitchen (Image: Runming Yao)

the building are intended to prevent overheating in summer and store warmth in the winter to be released slowly during cooler periods such as at night and on overcast days (Fig. 10.7)).

- The windows are triple glazed, while their timber frames further reduce heat loss. Well-sealed windows and doors and the concrete construction significantly reduce heat loss. A heat exchanger in the wind-driven ventilation system recovers between 50 and 70 % of the warmth from the outgoing stale air;

**Fig. 10.10** BRE innovation park (Image: BRE)

- Glazing predominantly faces due south to receive maximum solar gains. Unheated double-glazed sunspaces form an integral part of each dwelling. In summer, the outer windows open to create open-air balcony (see Fig. 10.6);
- Workspaces are in the shaded zones of the dwellings and lit by large triple-glazed northlights set between the roof garden;
- Specially designed rooftop wind cowls use the wind to draw warm stale air up from inside, and direct fresh air downwards over a passive heat exchanger (see Fig. 10.8);
- Heat exchangers in the passive, wind-driven ventilation system recover up to 70 % of the heat from outgoing stale air (Fig. 10.9);
- Kitchens are fitted with the latest energy-saving appliances and low-energy lighting allows the whole house to be lit (1 light per room) for a total power of 120 W.

*Performance*

The project is the first residential building scheme shortlisted for the *Stirling Prize* in the UK. It is estimated that residents might see a 60 % reduction in total energy demand and a 90 % reduction in heat demand, compared to a typical suburban home. According to the first year's monitoring, the project saved 88 % of energy consumption for heating, 57 % of energy consumption for hot water, and 25 % of the electricity demand.

**Fig. 10.11** Barrett Green House (Image: David Lim)

## *10.7.2* BRE Innovation Park

Located in Garston near Watford, UK, the Building Research Establishment *(BRE) Innovation Park* (Fig. 10.10) was opened in 2005. It features eight of the world's most sustainable houses and was designed to showcase the latest methods of modern construction with over 200 innovative and emerging technologies. The park serves as a test facility for selected construction companies and has an educational bias. The demonstration homes were built to meet the *Code for Sustainable Homes* (CSH) standard with some achieving level 6: the highest award.

One home on the park, and winner of the *2007 Home for the Future Design Award*, is the *Barratt Green House* (Fig. 10.11). 2 years in the design process, the three-story home is not only energy efficient, but its construction materials meet the BRE's *Green Guide to Specification* standards (see Chap. 11) and was designed for volume building in mind. Internally, furnishing and finishes use: low emission paint, natural fibers such as cotton, linen, wool, and silk, recycled plastics (some doors) and feature recycled glass, seen in its chandelier and all the domestic glass products within such as the vases.

*Energy Conservation Features*

- Triple glazing using insulated timber frames: to reduce heat loss;
- Heavy concrete floors: increase thermal mass to regulate internal temperature fluctuations;
- *Aircrete* masonry blocks: the walls are part constructed with these blocks using thin-joint mortar, again, to enhance thermal mass;
- Super insulation: uses 180 mm of *Kingspan K5 EWB* premium performance rigid phenolic insulation beneath a solid shell, creating a wall envelope with a U-value of 0.10 W/m/K;
- Solar power: Photovoltaic cells on the roof generate electricity for the home's equipment use;
- Computer control system: automates and optimizes many of the building services;
- Heat pump: the house is heated using an Air Source Heat Pump (ASHP) that uses low grade heat in the air and mechanical ventilation with a heat recovery system;
- Automatic shutters: the central control system automatically operates window shutters to reduce excess solar gains during the summer;
- Green roof: the north-facing roof is planted with vegetation. This enhances the local ecosystem and further insulates the roof;
- Solar thermal system: domestic hot water is provided by a solar thermal system to help achieve a code level 6 (CSH);
- Glazing ratio: there is glazing equivalent to 25 % of the total floor area. Window placement with this balance helps maximize solar gain while minimizing heat loss.

With regard to performance statistics, the home is currently undergoing a robust evaluation process with data being collected. As a demonstration project, it might be challenging to establish a true picture of its operation as visitors will behave differently compared to 'proper' occupants. Nevertheless, it will be interesting to assess energy and operation as an initial prototype for a volume build eco-home design.

### 10.7.3 The UCL School of Slavonic and East European Studies, Central London, UK

Formally opened in October 2005, the *SSEES Building* (Fig. 10.12) is part of *University College London* (UCL) and houses the *School of Slavonic and East European Studies* which includes a specialist library. The award winning, seven-story building is located in central London and features a groundbreaking hybrid

**Fig. 10.12** The new School of Slavonic and East European Studies (SSEES) at UCL (Image: David Lim)

environmental strategy: it is naturally ventilated year round and 'downdraft cooling' comes into play during warmer periods via the central light well—an extremely energy efficient method of maintaining comfort within the urban heat island.

Following thermal modeling, the stack ventilation strategy used for the building was supplemented with the introduction of *Passive Downdraft Cooling* (PDC) to cope with temperature extremes. As with passive techniques, this enables cooled air to be distributed throughout the building without mechanical assistance.

A large light well in the center of the building plan distributes air in and around it; the airflow reverses by season. Exhaust stacks located around the perimeter 'pull' air through and out of the building. The light well also allows daylight to penetrate deep into the building. Artificial lighting is provided by energy efficient *T5* luminaries with a full daylight linked presence detection control system.

A single triangular light well located in the center of the pan, bisects all floors, providing natural light as well as fresh tempered air in winter and passive ventilation cooling mid-season (Fig. 10.13). On the front elevation, a continuous double facade is used rather than individual stacks, which reduces traffic noise experienced at the rear. Transfer grilles enable the passage of fresh air from the core to the perimeter rooms. Both the stacks and the double facade have transparent elements on the outer and inner faces to permit the entry of daylight and to provide occupants with external views.

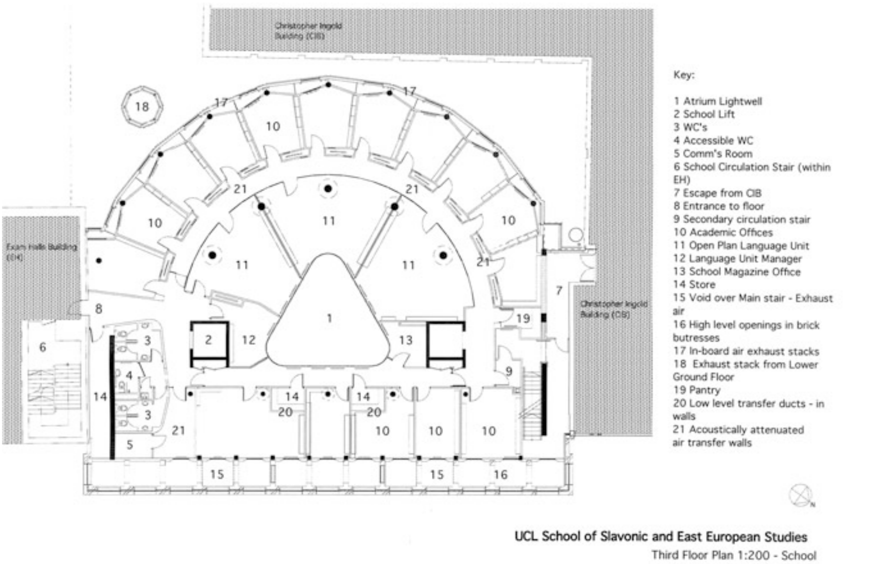


**Fig. 10.13** Triangular light well for daylighting and ventilation

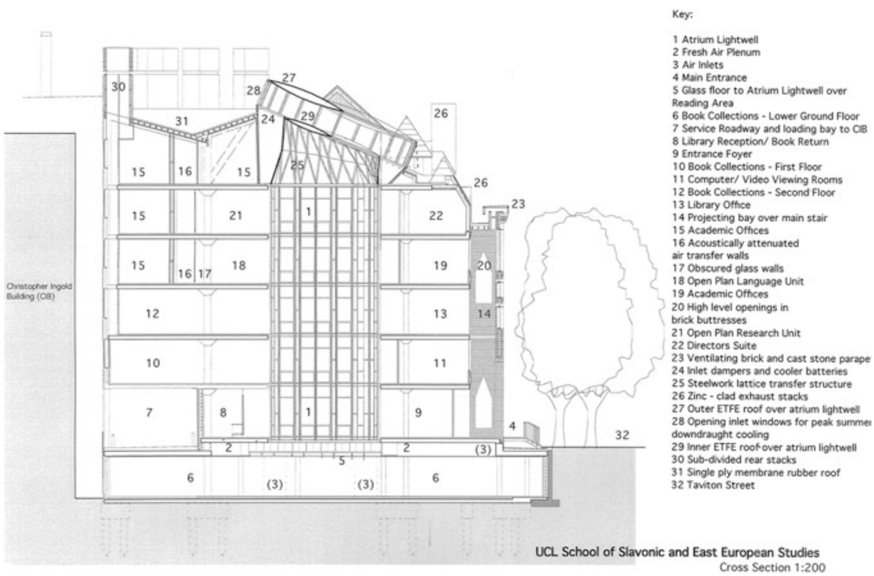


**Fig. 10.14** Cross-section of the SSEES Building, UCL, London

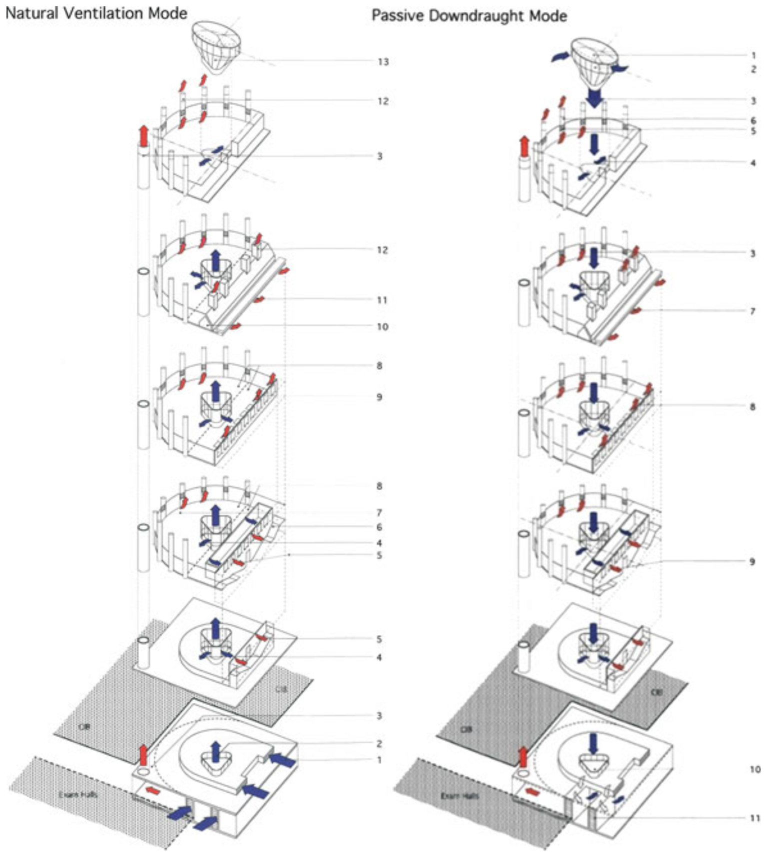


**Fig. 10.15** Exploded diagram of the light well operating in ventilation and downdraft modes

Microclimate studies demonstrated that a mechanism for cooling was required. The chosen technique involves admitting fresh ambient air at the top of the central light well, and cooling it so that it flows downwards, filling the space with a static reservoir of cooler dense air. The air can flow across 'floor plates' in a controlled manner, driven primarily by static pressure created by the cool air column. It is also assisted by internal heat gains, which should create a buoyancy-driven flow up the exhaust stacks and double façade.

The building has a hybrid environmental strategy; it is naturally ventilated all year round with passive cooling through the summer months, but engages downdraft cooling (via a central light well) when peak temperatures occur. The London 'heat island effect' shows the city center to be warming, but the SSEES project demonstrates that it is possible to configure a low-energy strategy in a city center at these latitudes.

Seasonal modes of operation:

*Winter*

Before occupancy, the building is warmed by finned emitters located around the light well and at the parameter of the building. All dampers are sealed closed. As the building is cocooned by the double facade and linked stacks (at the rear), the energy required to offset fabric heat losses is very low. During occupancy, air enters the base of the building from opposing orientations to satisfy the occupancy fresh air requirement. It is introduced into the base of the light well through dampers and across heating coils. In mid-season, air is admitted via the low-level plenum and the top of the light well is opened to provide the additional volumes of air needed for ventilation cooling.

In peak summer conditions, the windows and the ring of dampers above the cooling coils are open, allowing air to pass across the coils and directly into the light well (Fig. 10.14). The chilled water in the cooling coils lowers the temperature of the air, which falls freely, under negative buoyancy, filling the light well. The air then flows from the reservoir into each floor through conventional bottom-hung windows. The building has been thoroughly commissioned and monitored, a nontrivial task (Short et al. 2009) (Fig. 10.15).

## 10.8 Conclusions

Energy efficient design can deliver a host of benefits to building occupants; not least from reducing energy, carbon, and operating costs, but also improved indoor environments exemplified by enhanced air quality or thermal comfort. Achieving energy efficiency is primarily concerned with reducing energy demand in order to provide an equivalent (or better) level of building service. In part, this can be accomplished by using the principles of passive design/architecture. Governed by the laws of building physics, in particular, the ‘energy balance’, passive design takes advantage of conductive, convective, and radiative processes to achieve building services in the absence of mechanical or electrical systems. Passive solar heating, ventilation, cooling, and daylighting are all typical features that can be incorporated within contemporary eco-buildings. Furthermore, efficient buildings work in concert with the local climate, geography, and site characteristics in order to optimize the physical processes, which contribute to the efficient provision of services. Frequently, designers battle with conflicting design principles. When reconciling such conflicts, such as deciding upon the appropriate glazing ratio, sophisticated simulation tools are increasingly relied upon to help inform key decisions that are commonly encountered in the early design stages. Putting theory into practice, the inclusion of three case studies demonstrate a selection of energy efficient and passive design measures that enable low- or zero-energy building services.

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# Chapter 11
# Renewable Energy for Buildings

**Tony Day, David Lim and Runming Yao**

**Abstract** This chapter discusses the growing importance of integrating renewable energy technologies (RETs) into buildings, the range of technologies currently available, and what to consider during technology selection processes. A main section introduces the key principles relating to popular technologies, their functionality, and applicability; this includes: solar photovoltaics, solar thermal, heat pumps, biofuels, and small-scale wind. This chapter draws to a close by highlighting the issues concerning system design and the need for careful integration and management of RETs once installed; and for home owners and operators to understand the characteristics of the technology in their building. *Learning outcomes*: on successful completion of this chapter, readers will be able to: (1) Appreciate the growing importance of RETs and their application in the context of building integration; (2) Understand the principle mechanisms for their deployment in the built environment; (3) Gain insight into the range of technologies available and a deeper understanding of the popular technologies including: solar photovoltaics, solar thermal, heat pumps, biofuels, and small-scale wind; (4) Grasp the key concepts involved in selecting the most appropriate technology (mix) for a building; and (5) Know about the issues facing building owners and operators once a technology(s) has been installed.

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**Keywords** Implementation · Micro-generation · Renewable energy technology

## 11.1 Introduction

Renewable energy technologies (RETs), also known as renewables, green technologies, or low and zero carbon technologies (LZCs) are increasingly seen as an important way to reduce carbon emissions and fossil fuel demand from buildings. In developed countries, buildings are responsible for up to 50 % of carbon dioxide ($CO_2$) emissions, suggesting a significant opportunity to make savings by generating and supplying LZCs energy close to point of use or integrated within a building. Intelligent use of RETs should be part of a fully integrated strategy of reducing demand through energy efficiency measures and effective building design. Nevertheless, renewables cannot be viewed as a simple technology fix for buildings with high energy demands.

The general definition of a renewable energy *source* is one that derives energy from a non-depleting resource. This is to say that the rate at which energy is extracted is balanced by energy flowing into that resource. At the highest level, renewable energy sources derive mainly from solar energy (solar, wind, wave, and bioenergy) or gravitational energy (tidal, action of moon and sun on the oceans). Geothermal energy is also usually considered renewable, although technically this extracts heat from the (very large) nonrenewable heat store within the planet. In contrast to fossil fuels that will eventually deplete, renewable energy will not, as the term suggests. They also emit little or no (net) $CO_2$.

A major drawback with RETs is that their operation, which is dependent on natural resources, is often intermittent, or not constant. For instance, the sun sets at night and wind speeds are variable. This means that RETs either have to store energy or work in concert with more reliable sources of energy supply like fossil fuels or nuclear power. These issues of size and storage inevitably impact on cost, as RETs are currently considered an expensive means of reducing carbon emissions in buildings.

These issues present significant challenges when applying renewable energy to buildings. This chapter concentrates on those technologies that can be integrated into buildings and building developments, rather than large-scale renewables that supply the electricity or gas networks. We will look at the typical technologies in use today, their particular engineering, and the design challenges associated with them.

## 11.2 Policy, Regulations, and Planning Requirement

The relatively high cost of most RETs means that wide-scale adoption needs a legal requirement or an incentive; in some countries, there is a mix of both. The introduction of the UK Climate Change Act 2008 (DECC 2008) has created a mandatory requirement for the country to reduce its carbon emissions by 80 % by 2050 on 1990 levels. In addition, the 'EU 20-20-20' targets (20 % cut in greenhouse gas emissions, and 20 % increase in use of renewable energy, and 20 % cut in energy consumption through improved energy efficiency, all by 2020) have placed an increasing importance on RETs and their uptake.

Part L of the UK Building Regulations (DCLG 2010) specifies carbon emission targets for new and refurbished buildings that are very challenging to meet unless one or more RETs are incorporated within the design. Standards have progressively tightened over the years, and in 2016 all new domestic buildings must be zero carbon (2019 for nondomestic).

Another mechanism used to bolster RET uptake is planning legislation. UK Government planning guidance was in the form of the planning policy statement (PPS), with RETs addressed in PPS 1 (Sustainability) (DCLG 2005), and PPS 22 (Renewable Energy) (DCLG 2004). This requires local planning authorities to include policies encouraging low-carbon developments and increase renewable energy provision (e.g., *The Merton Rule*, where all new developments had to provide 10 % of their energy needs using on-site renewables). A more sophisticated version of this approach was adopted by the greater London authority (GLA) through the *London Plan* in 2004 (GLA 2004). This developed a hierarchy of carbon reductions for all new developments, referred to by the London Mayor as: 'be lean, be clean, be green' (Fig. 11.1). In essence, this required new buildings to demonstrate emission reductions from a base line (set by Building Regulations) using efficiency measures (be lean), followed by efficient energy provision from combined heat and power (CHP) (be clean), and finally, reducing emissions by a further 10 % through on-site renewables (be green).

Policy performance reviews were conducted to show their effectiveness (Day et al. 2010). Following such studies, there is now a greater understanding of what approaches work for particular development types, and what does not work.

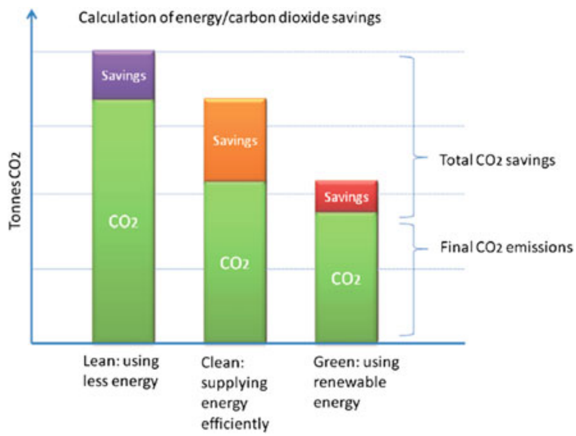


**Fig. 11.1** The London Mayor's energy hierarchy (*source* CoW 2009)

## 11.3 Renewable Energy Technologies

This section looks at the range of RETs that are commercially available, comments on how to select them, and provides an overview of their functionality and applicability for a selection of popular technologies.

RETs commonly considered for buildings integration include:

- Air source heat pumps (ASHP), for heating;
- Ground source heat pumps (GSHP), heating and cooling;
- Ground coupled cooling (GCC), including river and bore hole water;
- Biomass boilers;
- Micro-hydro electricity;
- Combined heat and power (CHP), renewably fueled;
- Solar photovoltaic (PV);
- Solar thermal (ST);
- Microwind turbines.

It is worth noting the following: (1) heat pumps and GCC are not strictly 'renewable energy' as they generally require electricity; (2) biomass boilers might not be *wholly* renewable as they incur carbon emissions associated with fuel transportation, fertilizer use, and other biodiversity considerations; (3) renewably fueled CHP is generally powered by a particular biofuel, this could be solid biomass; however, this tends to restrict the technology to steam turbines; and (4) even technologies that convert freely available energy resources, chiefly solar and wind, will have associated carbon emissions (and other environmental impacts) from their manufacture and installation.

### *11.3.1 Renewable Energy Technology Selection*

Each technology exhibits particular characteristics which determine its use and suitability; it is therefore important to consider how that technology will work for a particular building. Several issues should be considered as this is not simply a question of how much energy a technology can provide. These include:

- Building type, function, and form;
- The building's energy demand;
- Building occupancy and usage patterns;
- Site access, plant space, and storage options;
- Local site and climate conditions;
- Synergies and conflicts between RETs;
- Regulation, planning, and other constraints and requirements;
- Shading from neighboring buildings, structures, and trees etc.;
- Capital and maintenance costs;
- Economic incentives.

Commonly, technology selection is made during the early design stages of a construction project. Indeed, the earlier this decision is made, the better. This is because design costs are generally reduced and it also helps to ensure that RETs are properly integrated within a building project. Early feasibility studies are essential to identify which RET solution should be put forward for technical design.

Planning compliance requires developers to submit an *energy statement* showing how they intend to meet legislative targets. Given that construction at this time is still at the conceptual design stage, detailed calculations are challenging as many factors are undecided. However, industry professionals use ‘rules of thumb’ and past experience (of which there is a growing body of evidence) to gage carbon savings.

There are also other general rules which apply. For example, it is generally inappropriate to combine CHP with another heat generating technology (e.g., GSHP or ST). This can seriously undermine the economic viability of CHP. On the other hand, it is often effective to combine PV with another technology. This is because any excess electricity can be exported to the grid and will therefore always have some value. A typical dilemma, or trade-off, can occur when technologies compete for physical space. For instance, a building’s roof may be ideal for either PV, ST, or both: what is most appropriate? Optimization calculations are possible based on area, cost, and returns, but become very complex when multiple RETs are considered. Software has been developed for such tasks, but requires a reasonable level of sophistication, as well as pragmatic decision making, to derive the best solution. Needless to say, it should always be expected that, solutions put forward at the feasibility stage will likely change during technical design.

## 11.4 Photovoltaics

Photovoltaics (PV), also known as *solar PV* or *solar panels*, consist of PV cells that convert sunlight directly into electricity via the *photovoltaic effect*. This is a quantum level phenomenon whereby solar energy (photons) striking a PV surface (semiconductor) ‘knocks’ electrons loose from their silicon atoms, allowing them to flow around an external circuit to create a difference in electrical potential across a cell. This generates a direct current (DC) which is generally converted into an alternating current (AC) with an inverter. Unfortunately, the voltage created by a single PV cell is very small (1 or 2 V) so cells are connected together in *series* to form ‘strings’ which then provide a useful working voltage, normally 12 V. These strings (cells) are often placed in a frame for structural support to form a panel. Panels are typically designed for a peak electrical output of 40–50 Wp (Wp = peak Watt: the design output under optimal solar conditions). A number of panels are then connected together in parallel *arrays* to provide higher power outputs.

The marketplace holds a variety of PV cell types, all with differing characteristics and conversion efficiencies. Table 11.1 shows the typical efficiencies and types of cells.

**Table 11.1** PV cell types

| PV cell type | Typical efficiency (%) | Comments |
|---|---|---|
| Concentrator | 40 | Still in development, not commercially available |
| Monocrystalline | 16 | Very common |
| Polycrystalline | 8–12 | Very common (cheaper option) |
| Amorphous | 6–10 | Common |
| Thin films: Cadmium telluride (CdTe) and copper indium diselenide (CIS) | 7–9 | Often the cheapest option, can be curved and therefore useful for building facades |

Historically, system efficiencies are improving over time with new methods of manufacture and use of materials continually reducing costs. In recent years, volume manufacture and economies of scale have also led to a reduction in cost. Furthermore, where PV replaces traditional roof cladding, say concrete tiles, the avoided cost can be factored into the cost/benefit analysis.

### *11.4.1 Mounting*

PV cells can be affixed to buildings in a variety of ways; this is largely dependent on the characteristics of the building envelope and type of application.

Roof top mounting is most common and largely influences the PV array specification. In the UK, south facing is ideal with up to 15° (east or west) making very little difference to energy yields. The other key influencing factor is roof pitch (steepness); the ideal angle being between 30° and 45°, but anything from 10° to 50° is sufficient in most situations (Fig. 11.2).

There are also *PV slates* that are manufactured to look like traditional slate roof tiles (Fig. 11.3). Although these have lower efficiencies, their use is often permissible on listed buildings.

Flat roofs are also suitable for PV mounting, but special attention is required to ensure no damage occurs to the roof waterproofing system. An advantage of a flat roof installation is greater flexibility in fixing orientation and pitch angle to suit the location.

### *11.4.2 Facades*

An alternative to conventional PV panels is *laminated glazing systems*. This method allows PV cells to be incorporated into building facades (Fig. 11.4) and roof lights. Such an approach increases the available area for PV greatly. Disappointingly,

**Fig. 11.2** Roof top mounted system

**Fig. 11.3** PV slates

vertical installations have much lower energy outputs per square meter (kWh/m$^2$) than roof top systems: up to 40 % less in London (Day and Moore 2011).

### *11.4.3 Shading*

Unsurprisingly, *solar shading* (full or partial) caused by trees, buildings, and other structures considerably reduces energy output. Naturally, solar evaluations should also consider the physicality of smaller objects (e.g., roof hand rails, building services structures) and larger objects too, such as buildings that might be constructed in the future.

Interestingly, some PV systems assume a dual purpose: electricity generation *and* solar shading. Unwanted solar gains can be reduced by shading from the PV panels themselves, thus reducing the energy from space cooling demands.

**Fig. 11.4** PV facade

## *11.4.4 Modeling, Performance, and Economics*

The decision whether to install PV and the system specification is generally influenced by economics. As such, computer models are commonly used during early design stages to estimate energy output and conduct economic assessments. The annual variance of insolation due to both solar positioning and cloud cover, the effects of location, orientation, and other conditions, necessitate the need for robust models to account for all these factors. Free tools such as RETScreen (NRC 2011) can be obtained or more advanced tools such as PV*SOL Pro (SDC 2011) or PVsyst (PVsyst 2011) can be purchased.

The key output from these tools is the annual energy yield (kWh or kWh/kW$_p$). The unit 'kWh/kW$_p$ is the energy yield per peak kilowatt installed. This metric is useful for comparing the performance of a system against existing systems of known performance and differing sizes. For the UK, this value is often quoted as 800–850 kWh/kW$_p$, but one study looking at ten sites in London showed an average of around 660 kWh/kW$_p$ (Clarke and Day 2012).

Other important factors are the cost of the system (£/kW$_p$) and the value of the generated electricity. The value of the electricity can depend on a number of issues. First, the electricity generated on a site will most likely avoid the import of electricity from the grid, so the avoided costs on electricity bills (in p/kWh or £/kWh) are taken into account. In addition, some countries, the UK included, pay a premium for every kWh of electricity generated. This could be a feed in tariff (FiT) (DECC 2010) or similar subsidy mechanism. Furthermore, if the installation generates surplus electricity, it is possible to export back to the grid and receive additional payment. Feed in Tariff structures are normally such that export electricity is not as valuable as avoided import.

## 11.5 Solar Thermal

Solar thermal technology is usually confined to the heating of domestic hot water (DHW), or low temperature applications such as swimming pools. While the efficiency of these systems range between 40 and 70 %, they generally operate better during summer months when space heating demand is low (for wet heating systems): this results in there only being a real demand for DHW. For an in-depth understanding behind the theory and design of ST systems, readers are directed to Duffie and Beckman (2006). It is also possible to use high efficiency, high temperature collectors to power absorption chillers to provide cooling. Currently, this is very expensive and is only applicable for countries with hot climates.

Typical ST systems for domestic applications comprise of 4 $m^2$ of collector area, connected to a twin coil hot water storage cylinder. The solar collectors are connected to the lower heating coil, while the back-up heater (normally a gas boiler) is connected to the upper coil. This arrangement provides most of the hot water demand in sunny conditions, but also provides some preheat during cloudy days for instance.

For larger applications (e.g., hotels), dedicated ST hot water storage tanks are commonly used. These operate in series as a preheat with either traditional DHW calorifiers or with dedicated back-up water heaters.

Essentially, there are two main types of ST technology: *flat-plate* collectors and *evacuated tube* collectors.

### *11.5.1 Flat-Plate Collectors*

Flat-plate collectors (Fig. 11.5) are simpler and cheaper than evacuated tube collectors. They consist of a thin (10 cm) rectangular box with three main components: (1) a front absorber plate (usually dark in color) that is usually covered by a transparent cover (glass or polycarbonate) to reduce convection losses; (2) a heat transport fluid (e.g., brine, water, or antifreeze) running through tubular pipes sandwiched between the plates to transfer heat; and (3) an insulated back plate. Principally, solar energy is converted to heat energy, warms the fluid which transfers the heat to an insulated water tank, sometimes with the aid of a pump. Flat-plate collectors can achieve flow temperatures of up to 90 °C with intense sunlight, and can provide warm water even in overcast or weaker solar conditions.

**Fig. 11.5** Flat-plate collector

**Fig. 11.6** Evacuated tube collector on a domestic tiled roof

## *11.5.2 Evacuated Tube Collectors*

Evacuated tube collectors, also called *vacuum tubes* (Fig. 11.6), consist of glass cylinders that have a partial vacuum in them to eliminate any conduction losses. The cylinders have thin *absorber plates* (which look like coated finned tubes) running through the middle of them. Each absorber plate contains a heat transfer fluid that operates on the principle of a heat pipe. Solar energy heats the pipe, turning the fluid into vapor where it rises to the top of the pipe where it becomes hot. The heat is then transferred to a DHW or hydronic space heating system, consisting of water or an antifreeze mix (e.g., propylene glycol) in a heat exchanger or *manifold*. After the heat is extracted, the fluid condenses then runs back to the bottom of the absorber plate to restart the cycle. The reduced losses mean that evacuated tube collectors are more efficient than flat plates, and can provide useful heat over more of the year. They are, however, significantly more expensive.

### *11.5.3 Mounting and Installation*

Solar thermal collectors are best mounted in a similar fashion to PV systems: on the roof of a building, nearing ideal orientation and pitch. On pitched roofs, they are attached to structural roof members and are positioned on top of the tiles or slates. There are some systems whereby the panels are an integral part of the roof, but these are not yet common.

On flat roofs, it is important to mount flat plates in a suitable frame to provide the optimum tilt angle to capture maximum solar radiation. For evacuated tubes, this is less important. They can be laid flat on the roof surface, while the absorber surfaces themselves are tilted within the glass tubes to enhance collection. This can make evacuated tubes visually less obtrusive.

### *11.5.4 Modeling, Performance and Economics*

As with PV, ST systems suffer from the uncertainty of timing and magnitude of solar energy from the sun. In addition, the mismatch of heat supply and heat demand is a complex issue as ST systems cannot ‘export’ excess supply (unless attached to a heat network, but this is very rare) like a PV system. Therefore, heat needs to be stored, or as explained above, dissipated and ‘thrown away’. Storage is expensive and requires space, but where possible, this is by far the best way to match solar supply with a variable demand pattern. There are systems that use phase change materials for storage, but there are problematic issues with temperatures and heat exchange which need to be fully resolved for many of these.

ST systems replace the need for fossil fuel generated heat, typically gas, which has far less value than electricity. While the efficiency of ST panels is greater than PV, and therefore providing greater energy savings, the cost of gas is typically one-third to one half of electricity, resulting in reduced financial savings. Nevertheless, the installed cost for the ST collector will be less than PV panels, perhaps less than half in terms of £/$kW_p$. Heat is less carbon intensive than electricity (if supplied by natural gas), leading to lower carbon savings per installed $kW_p$ than renewably generated electricity.

## 11.6 Heat Pumps

As previously mentioned, heat pumps are not strictly a renewable energy technology. A heat pump (when in heating mode) is effectively a refrigerator operating in reverse—pumping heat into a building, rather than pumping it out. Some have reverse operability, whereby cooling a building, similar in operation to a conventional refrigerator. So how do they work?

A heat pump transfers heat from a low temperature heat source (e.g., ground, water, or air) to a higher temperature load (i.e., the desired indoor temperature). To do this, it needs a higher grade energy input, such as electricity or high-temperature heat, to make the transfer possible. The advantage is that for every unit of energy it consumes, it can transfer several units of heat from the source to the load. This ratio of delivered heat to energy input is known as the coefficient of performance (COP): a concept commonly used in engineering.

A heat pump's COP is highly dependent on the temperature difference between the source and of the load. The smaller this difference, the less input energy is required to transfer energy from source to load and the higher the COP value. For this reason, heat pump systems aim to find relatively high source temperatures, and aim to deliver low temperature to the building. This last point has implications for the retrofitting of heat pump systems, and for the design of heating systems in buildings generally.

Undoubtedly, the most common type of heat pumps use electricity to drive vapor compression cycles; these cycles are only briefly covered in this chapter. As electricity (in the UK) has a relatively high carbon intensity (around 0.53 kg $CO_2$/kWh), it is important to maximize the COP of the system if carbon savings surpass that of traditional gas-fired boiler systems. The UK Building Regulations state that heat pumps must have a minimum COP of 2.2. In theory, heat pumps should be able to achieve substantially higher values than this approximately 3–4 giving them a substantial carbon advantage over gas boilers. It is unfortunate that various practical constraints often limit the overall COP.

### *11.6.1 Ground Source Heat Pumps*

Depending on latitude, ground temperatures become relatively constant throughout the year (10–16 °C) at a depth of 4 m or more. The ground therefore provides a good temperature source and there are many ways to tap this resource. First is the use of an *open-loop* system. This uses bore holes to extract ground water which is then put through a heat exchanger via a heat pump. The water is returned to the ground at a lower temperature, either close to the extraction point or remote from it. Water extraction systems such as this require a licence from the Environment Agency in the UK as they can have a range of potential environmental impacts.

The alternative is a *closed-loop* system, whereby water is circulated through pipes which run down into the bore hole. In this way, no water is extracted from the ground. Another, and increasingly common method, is to run the pipes in the pile foundations of a building (sometimes called *thermo-piles*); this is particularly attractive in dense urban sites where land access is restricted. The other type of ground source is the use of horizontal collector pipes. This entails laying pipes, straight or coiled (slinky), in shallow trenches in land adjacent to the building. The advantage being, at this depth, summer solar energy restores the ground heat and temperature, ready for harvesting in the winter. As one might expect, this is seldom appropriate for urban situations and will usually be confined to properties with large available land area close by.

### 11.6.2 Air Source Heat Pumps

While the ground provides a stable heat source, the cost of drilling bore holes, installing pipes in piles, or laying pipes in the ground can be expensive; and retrofitting GSHP to existing buildings (particularly in urban areas) is often not practical. The alternative is ASHP. Air source heat pumps which extract heat from ambient outdoor air conditions are applicable to most building types, and equipment and installation costs are both cheaper than GSHP.

There is one obvious drawback: low external air temperatures. As described, larger temperature differences across the heat pump increase the required electrical input, and therefore reduce seasonal COPs to a level lower than GSHPs. The seasonal COP is therefore strongly dependent on climate, so predominantly cold climates (e.g., Scandinavia) tend to be unsuitable for ASHPs. This situation is compounded by the need for defrosting of the evaporator (heat collection) coil. In order to absorb heat, the temperature of the evaporator must be lower than the outdoor air; so at outdoor temperatures below approximately 5 °C, the evaporator can be below freezing point (0 °C). This will cause any moisture in the air to freeze on the evaporator surface, which ultimately restricts air flow and heat exchange. The heap pump must have a defrost cycle to periodically remove this ice, which becomes a further energy penalty, which reduces COP even further.

One trial of 28 domestic scale ASHPs showed that 50 % of the units struggled to get COPs above 2.0 (EST 2010), while GSHPs showed better performance. ASHP systems are constantly improving, innovative solutions have been developed to improve their operating efficiency, and future projections estimate seasonal COPs to exceed 3.0.

### 11.6.3 Load Side Considerations

In order to maintain high COPs, it is necessary to keep the delivery temperature (i.e., the space heating set point) to a minimum. Traditional gas- or oil-fired central heating systems operate at flow temperatures of 70–80 °C. However, heat pump systems need to operate below 50 °C to remain efficient. This has implications for the design of heat distribution within the building, with larger heat emitters, and perhaps larger pipes and pumps. For retrofit applications, this requires a close look at the existing distribution system to make sure it can provide adequate heat output at lower system temperatures.

The other consideration is DHW, which needs to be stored above 55 °C to prevent the growth of legionella bacteria (the cause of Legionaire's Disease). While it is possible to exploit some of the heat pump output to deliver the required temperature, this is unsustainable without auxiliary heat from other sources. For domestic applications, this is typically an electrical immersion heater, and the resulting electricity consumption needs to be factored into COP calculations. Larger commercial installations may use dedicated gas water heaters. In light of this, an efficient technology combination is: heat pumps to provide space heating and ST (with fossil fuel top up) to provide DHW.

### *11.6.4 Ground Coupled Cooling*

Exploiting the difference between ground temperature and ambient air temperature during summer months, can result in provision of cooling for buildings. There are a variety of options to facilitate this.

*Bore hole cooling* delivers cool water (at around 10 °C) to heat exchangers that distribute cooled water or air around the building. COPs for bore hole cooling can be very high (up to 70), as the energy required to provide the cooling is from the bore hole pumps, and any additional circulating pumps required is from the building itself.

Variants of bore hole cooling can employ surface water from rivers, lakes, or even the sea. Surface water will be warmer than bore hole water, with subsequently poorer cooling capacity, but it can provide a lower cost option. Unfortunately, there is a slight drawback in that water systems require significantly more maintenance to keep them clean and free from blockages.

Another method is the use of reverse cycle heat pumps in conjunction with thermopiles, briefly discussed above. At the end of the heating season, the ground store will be at its lowest temperature–perhaps as low as 5–7 °C. When heat pumps switch to 'cooling mode', the ground becomes the heat sink, which at these temperatures, ensuring that good cooling COPs can be achieved. Ground temperatures recover during summer and heat is stored; however, if the ground temperature exceeds typical ambient air temperature, then it is necessary to have an *air cooler* or *cooling tower* to remove excess heat from the building in the way of traditional chilling systems. If a building has been designed with a good seasonal heat balance, this heat 'dumping' will be unnecessary, and the high ground temperatures at the start of the heating season will provide exceptionally good heating COPs. This type of system should perhaps be seen less as renewable heat and more as recycled heat.

## 11.7 Biofuel and Biomass

*Biofuel* is a term that describes fuels derived from relatively recently grown plant matter. These fuels include: wood (lumber), biodiesel, bioethanol, and bio-gas. *Biomass* is the term that defines the actual feedstock for biofuels. For example, the feedstock for bioethanol is sugar cane or cereal grain. Perhaps the most common biofuel used in buildings is in the form of wood fuel (e.g., logs). This is probably the first thought, conjured up in people's minds when asked about biomass for building applications.

### 11.7.1 Wood Fuel and Biomass Boilers

Specific wood fuel for biomass burners assumes two forms: *wood pellets* and *wood chips*. Wood pellets are a wood-derived fuel originating from a variety of sources (e.g., waste and virgin wood) that are ground to sawdust and compressed into solid pellets. These have a relatively high energy density of 18 MJ/kg, and the manufacturing process allows good control of moisture content. However, this is a more intensive production process than the alternative wood chip. Wood chips tend to derive from the chipping of virgin timber grown especially for this purpose. This wood needs to be suitably seasoned and dried in order to reduce residues on burning, and to ensure a good calorific value. Wood chips, being less dense than pellets and irregular in form, require greater storage space than pellets, and may have a more variable moisture content (influencing the heat content).

Biomass boilers tend to be designed to handle a particular type of fuel. Increasingly easier to use, modern boilers are fully automatic in terms of fuel feed, output regulation, and shutdown etc., and have reached very high levels of reliability. As expected, the heat output of biomass boilers cannot be regulated as fast as gas or oil burners, which can lead to problems, where rapidly fluctuating heat demand patterns occur. This is overcome by the use of a buffer vessel in the heating system that allows the boiler to be relatively unaffected by the heating system fluctuations. In some larger schemes, large heat stores are required to manage load variations.

Inclusion of a biomass boiler is a simple means of satisfying carbon saving targets, particularly those imposed by planning requirements discussed earlier. The technology is an attractive option because it provides heat in the same way much as conventional gas- or oil-fired boilers that operators are familiar with. They are often sized to meet a building's space heating *base load* demand, with gas or oil boilers as top up. This approach is advantageous, whereby immediate load fluctuations are managed by the more responsive boilers, which reduce need for a heat store. On occasions, however, this can lead to cases where the biomass boiler is never used: boiler plant is normally oversized, and fossil fueled boilers can often meet majority demand, in which case users invariably stick with what they know—fossil fueled systems!

### 11.7.2 Storage and Access

One of the key issues, and barriers, with biomass boilers is whether there is sufficient space for fuel storage. Storage requirements should be gaged on fuel delivery frequency and the security of heat supply. For example, a hospital relying wholly on a biomass system will need a large fuel store to safeguard against failure of delivery in poor weather conditions.

Wood chip stores require more space than pellets due to their lower density. There is also a danger of spontaneous combustion of wood in poorly designed stores due to heat generation from natural organic breakdown in the store (similar to composting).

Site access is an important consideration as fuel delivery can involve heavy lorries, and consequently, the number of deliveries may be influenced by ease of access and nuisance to the surrounding neighborhood. It should also be remembered, that transportation, particularly delivery distance, incurs secondary carbon emissions (unless the truck fleet runs on biodiesel). Fewer and larger deliveries will be more cost and carbon efficient, but will require greater storage volumes and appropriate access roads.

Delivery into the store is normally achieved by attaching a flexible duct from the lorry and blowing the pellets or chips into the store. This makes delivery a relatively clean and a less disruptive operation.

### *11.7.3 Biodiesel and Biogas*

The use of liquid and gaseous biofuels is not yet common in building applications. Biodiesel is best used in CHP plant to deliver electricity and heat (Fig. 11.7) (Yao et al. 2006). Sizing and selection of CHP is beyond the scope of this chapter; but where this can be made to work, considerable carbon savings can be realized. Issues exist around sourcing of the fuel (see below) and storage.

Biogas arises from the process of anaerobic digestion (AD). Waste organic matter (food waste in cities or agricultural waste in rural areas) can be used as a feedstock to produce largely methane. This biogas can be used in the usual way, but it is best employed in gas-fired CHP engines. The problem is that AD

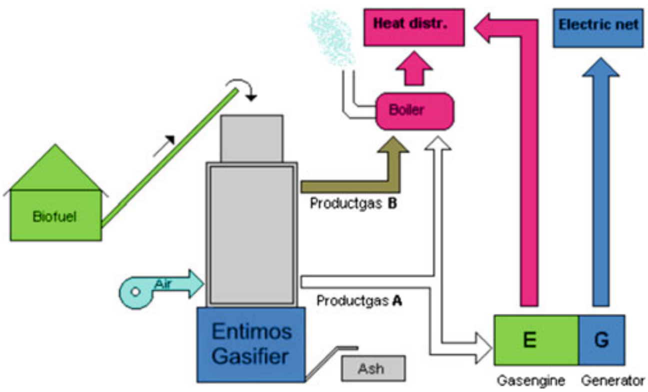


**Fig. 11.7** Biomass process in CHP (Yao et al. 2006)

processing plants are large and expensive. For example, one study showed that a 100 kW CHP engine would require the food waste from 11,000 homes. This is currently unviable, unless large centralized facilities can be developed.

### *11.7.4 Sources of Fuel*

The source and availability of biofuel is an important consideration. The transportation of fuel will incur environmental impacts, so ideally fuel source should be close to the point of use. This is uncommon, especially for demand in large cities. Biofuels require large areas of land to produce viable and sustainable crop yields. This land often has to compete with the needs of food production, and growers face ethical and economic choices regarding what they should be producing. These pressures can lead to biofuel production being remote from the end-use, and it may be that fuel availability will change over time due to market conditions. It is strongly advisable to fully research long-term supply-chain resilience and security to ensure biofueled installations are operable throughout their lifetimes.

There are instances where both wood and liquid biofuel imports are necessary. There is deep concern that the demand for bioenergy in the developed world is leading to deforestation, and there is encouragement of unsustainable monocultures in the developing world (e.g., palm oil plantations). This may provide economic benefits to those producer economies, but they could be using the resulting fuels locally rather than importing oil themselves.

A maelstrom of complex economic and ethical arguments prevails; nevertheless, design teams responsible for renewable energy solutions must be aware of such arguments.

## 11.8 Small-Scale Wind

Small-scale wind, also known as *microwind*, exploits the Earth's natural wind resource by utilizing wind turbines (microturbines) for practical purposes like generating electricity, charging batteries, pumping water, or grinding grain. Here, we only consider the application of building mounted wind turbines that range in size from a few hundred watts (power generating capacity), up to tens of kilowatts; although typical sizes range from around 1–10 kW.

The output of a wind turbine is given by Eq. 11.1.

$$P = 0.6 C_p A v^3 \tag{11.1}$$

where: $P$ is the power output in watts, $A$ is the swept area of the blades, $v$ is the free stream wind velocity, and $C_p$ is the power coefficient.

This equation tells us two important things about wind energy: first, that the power output is proportional to the cube of the wind speed; and second that output is proportional to the square of the length of the blades. Theory also tells us that we cannot convert more than 59.3 % of the kinetic energy in the wind into mechanical energy by turning a rotor—this is known as the *Betz Limit*. This power coefficient is also related to the wind speed and the rotational speed of the turbine, also known as the *tip-speed ratio*.

A turbine's *rated wind speed* is that in which the turbine was designed to run with an optimal tip-speed ratio. Above their rated wind speeds, wind turbines have maximum power outputs (the rated power) that cannot be exceeded. For small-scale machines, this is typically around 10–12 m/s. A useful description of the performance of a wind turbine is its *capacity factor*. This is the ratio of the actual electricity generated in a period of time to the maximum amount it could generate at its rated power output. So for example, a 6 kW machine could generate a maximum of:

$$\frac{8760}{1000} \times 6 = \frac{52.56\ \text{MWh}}{\text{year}}$$

If it actually generated 10 MWh, then this would have a capacity factor of:

$$\frac{10}{52.56} = 0.19\ (\text{or } 19\ \%)$$

Trials of some urban wind turbines have seen capacity factors of 8–10 %. This value will depend on a number of factors: the local average wind speed, any local obstructions, the turbulence of the wind at the site, and the type of turbine used.

It is essential to know the wind speed characteristics at the considered location in order to conduct an economic analysis. Ideally, hourly averaged wind speed data for an entire year is desirable, but this is rarely possible to obtain. To overcome this, statistical techniques are used to provide good approximations for annual frequency distributions which are used to calculate the expected output form a turbine. Mounting a turbine on a city building clearly imposes practical limits on size: likewise, city centers are usually in low lands that are not particularly windy and typical wind patterns exhibit significant turbulence.

Wind turbines are generally more expensive to mount on a building than ST or PV technologies. The wind imparts strong forces on the turbine, which are then transferred to the building structure. A full structural loading assessment needs to be carried out to ensure the correct mountings are fitted, which can also add to the cost of installation. As the force on the turbine increases with the square of the turbine blade length—as does the power output—there is a trade-off between maximizing power and minimizing the cost of installation.

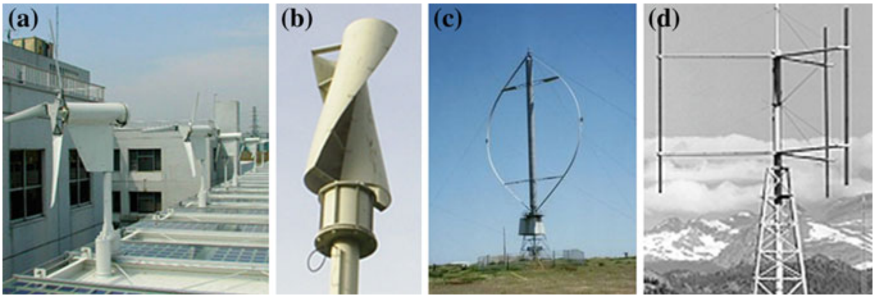


**Fig. 11.8** Turbine types, **a** HAWT; **b** Helical turbine; **c** Darrieus-rator; **d** H-Darrieus-rator

### *11.8.1 Turbine Types*

There are two predominant types of wind turbine: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Horizontal axis turbines (Fig. 11.8a) are more common, but there has been growth in small-scale vertical axis machines in recent years (Fig. 11.8b–d). Horizontal axis machines need to be able to face the direction of the wind, and a mechanism is required to achieve this which may affect the response of the turbine. Vertical axis machines do not require this, and are better suited for urban locations. However, their poor starting torque characteristics often require a motor to get them moving at the *cut-in* wind speed.

### *11.8.2 Planning Considerations*

Wind turbines create a greater visual impact compared with other types of building integrated renewables. The move toward vertical axis machines has been driven partly by esthetic considerations about what looks good in the urban landscape.

Another planning consideration involves *flicker*—the shadow cast by a turbine from the sun. This can be irritating, especially if shadows project onto occupied properties. An assessment of the turbine shadow path will have to be made if this is to be avoided.

Planners are also concerned with noise. Noise from turbines originates from two sources: the aerodynamic noise of the wind interaction with the blades, and mechanical noise from the gear box or generator. Noise is a sensitive issue and can be difficult to prove, especially in a noisy urban environment, but perceptions and preconceptions can be powerful entities to dispel.

Environmental pressure groups and the RSPB regularly voice concerns with birdstrike. This, as it reads, involves birds being hit by turbine blades which some organizations feel is unjust and poses a potential risk to wildlife.

Vibration to the building is another aspect, caused by wind load on the turbine. This can normally be reduced to negligible levels or eliminated entirely by suitable antivibration mountings. Failure to get this right, however, can result in nuisance vibration noise throughout the structure, and in severe cases, lead to damage to the building.

## 11.9 Design and Integration

The choice of which RETs to incorporate into a building, whether new or retrofit, must be carefully considered. The earlier this occurs within the design process the better. As we have seen, some renewables can be incorporated into a building faÃ§ade (e.g., PV), while others require dedicated foundation designs (e.g., GSHP). Therefore, altering designs late into the construction process usually adds significant cost. For this reason, feasibility and scoping studies must be conducted, ideally *before* building forms are fixed, and certainly before surface finishes or structural details have been selected.

This can create problems as design teams do not always include a renewable energy expert (typically an engineer) at early design stages. Even if an expert is present, it can be challenging to assess the most appropriate technology mix for a building. The design process should therefore involve iterations, or scenarios, which look at the impact of possible design outcomes. For example, the orientation of a building may be changed to maximize the opportunity for PV or ST; but if this cannot be done, it impacts upon the process.

Developing a ranking scheme for RET options is an advisable approach. This is based on known site conditions and constraints and any specific client requirements. Once the preferred technologies have been identified, then feasibility studies should be conducted. Note that some pairs of technologies do not typically function well together. For example, ST and CHP, GSHP and CHP which have overlapping heat demands, or PV and ST which often compete for space.

Feasibility studies can be conducted using simple rules of thumb, for example typical energy output per $m^2$ or $kW_p$ for an early evaluation; but it is better to use software tools to conduct more sophisticated analysis. Many tools are commercially available: some technology specific, others more holistic, while some have design optimization capabilities. The software approach is beneficial as it enables 'what if' analysis to be conducted to assess risk. Studies should include both carbon and cost-benefit analysis, as this is the basis upon which most design decisions are ultimately taken.

Following installation, it must be highlighted that the building owners, facilities managers, and operators must understand the specific characteristics, advantages, and disadvantages of the technology(s). Maintenance teams are still unfamiliar with the operational requirements of such systems, and many systems and components break down early on within their engineering lifetime because they are not checked or maintained adequately. If the failure of RETs does not result in a reduced service to the building, then this failure often goes unrecognized. For example, a ST system with top up gas boilers will always supply hot water even if the solar system fails. Likewise, the failure of a PV system will go unnoticed as the electricity grid usually makes up any shortfall. There are many examples of such failures which undermine the credibility of renewables in buildings, and undoubtedly compromise the intention and initial investments made. It is the duty of the design and installation teams to ensure that building users understand the value and novelty of these systems, and how they must be maintained to provide the cost and carbon savings they were promised at the design stages.

## 11.10 Conclusions

This chapter explains the growing importance of RETs, the policy mechanisms in place to bolster uptake, the range of technologies on the market, and how best to select them. Integrating RETs within buildings can help to contribute to the security of energy supply, meeting carbon reduction targets, and the sustainability agenda as a whole. However, RETs need to be selected and designed with care, integrated properly, and then operated correctly throughout their lifetime. Undoubtedly, this growing field is presenting a new set of challenges to the construction sector, and is bringing new skills, design thinking, and technical innovation.

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# Chapter 12
# Building Simulation

**Runming Yao and David Lim**

**Abstract** This chapter aims to provide an overview of building simulation in a theoretical and practical context. The following sections demonstrate the importance of simulation programs at a time when society is shifting toward a low carbon future and the practice of sustainable design becomes mandatory. The initial sections acquaint the reader with basic terminology and comment on the capabilities and categories of simulation tools before discussing the historical development of programs. The main body of the chapter considers the primary benefits and users of simulation programs, looks at the role of simulation in the construction process, and examines the validity and interpretation of simulation results. The latter half of the chapter looks at program selection and discusses software capability, product characteristics, input data, and output formats. The inclusion of a case study demonstrates the simulation procedure and key concepts. Finally, the chapter closes with a insight into the future, commenting on the development of simulation capability, user interfaces, and how simulation will continue to empower building professionals as society faces new challenges in a rapidly changing landscape. *Learning outcomes*: On successful completion of this chapter, readers will be able to: (1) Understand the benefits of building simulation tools and how they function within a construction process context; (2) Grasp the basic functionality, capability and range of simulation programs, and how best to select them; (3) Appreciate the key user categories and the benefits they can gain from using tools; (4) Comprehend the limitations and uncertainties of simulation

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results; and (5) Gain insight into how simulation tools have developed over time and how they might evolve in the future.

**Keywords** Building simulation tools · Energy performance · Modeling · Simulation programs

## 12.1 Introduction

Human evolution is testament to one of man's fundamental mile stones—the creation of tools. Putting this notion in a modern day context, *building simulation* can be considered part of this on-going success story. The word *simulate* originates from the Latin *simulare* meaning *to imitate*. Building simulation is a means of computationally *imitating* a building's performance. In other words, simulation can predict how a building might behave based on thermo-physical processes.

Buildings are complex systems. Their design requires careful consideration of multiple factors in order to deliver environments that optimize energy efficiency, foster health, and promote wellbeing. Building simulation is a way of considering the impact of a building's component systems and exists as an effective tool for assessing building services, new control strategies, costs, and sustainable features; ultimately, the outcome of which helps design teams make more informed decisions when considering the cost benefit of different design and refurbishment scenarios.

From an economic perspective, the benefits of building simulation cannot be over emphasized. In the majority of cases, simulation severely reduces the need for physical testing in order to verify design capabilities which would otherwise be time and cost prohibitive. However, if constructing the actual building is the only way of discovering the *exact* outcome of a design, then reducing financial risk becomes highly desirable. In addition to risk assessment, simulation tools can also determine life cycle costs and assess the impact of space use adaptation, such as converting retail space to office space. Likewise, the ability to simulate electrical load profiles allows financial departments to make informed value judgements when negotiating energy supply contacts too. In the dynamic world of construction, building simulation programs are incremental tools for assessment and invaluable for ensuring efficient work practices.

Architects, engineers, and consultants are frequently faced with key design issues: natural or mechanical ventilation; how to optimize daylight; what size of systems should be specified; what renewable energy technology is best suited or what is the optimal glazing ratio? Answers and clues to such questions emerge through building simulation. Furthermore, esthetic considerations and design constraints determined by codes and standards (e.g. building regulation), frequently leave professionals with having to strike a balance in a trade-off situation. Again, building simulation enables users to strike a 'better' balance by evaluating a design against a certain standard, while simultaneously assessing its esthetic quality.

As environmental considerations escalate, design standards for high performance buildings has led to increased levels of air tightness, insulation, and solar gain (Feist et al. 2005). Consequently, a building's heat balance becomes increasingly sensitive, requiring dynamic analysis for an accurate appraisal. Additionally, an obligation to build with high performance and sustainable construction materials has heavily influenced design and construction techniques. The birth of new phase change materials and insulated concrete formwork are typical examples, both of which can be successfully simulated. Furthermore, intelligent energy management systems bought about by advances in control technology, allow facility managers to finely tune environments enabling significant energy savings over the operational lifetime of buildings. To continue in this vein, industry must adopt an integrated design and analytical approach, one of which *building simulation* is ideally placed.

### *12.1.1 Building Simulation Programs*

The term building simulation is synonymous with other expressions including: building performance simulation (BPS), building energy simulation, building energy performance simulation, CAD, and building energy modeling. Essentially, the terms refer to the practice of using computer programs, or software, to provide an accurate assessment of how buildings perform under a given set of criteria. The assessment is often derived from complex algorithms encrypted within an elaborate mathematical model that quietly functions behind a graphical user interface (GUI). There are over 400 building energy simulation programs currently on the market. Their functionality is incredibly diverse; some cater for the analysis of single building elements, such as a beam, while others model the energy flows of whole cities. Each program is written in a particular language (e.g., C, C/, C++, Fortran) for a particular operating 'platform' (e.g., PC, Mac, UNIX, or Internet based), and is aimed at either an international, or country-specific audience.

### *12.1.2 Program Categories*

Building simulation programs can either be categorized by their *complexity* or by their *function*. When categorized by their complexity, four distinct categories emerge:

- *Simple Design Programs*
  Simple design programs are used for calculating basic metrics such as aggregated energy consumption, heating and cooling loads, and peak loads. They require limited data input, provide indicators influencing early design decisions and are commonly used for concept design;

- *Advanced Design Programs*
  Advanced design programs are used for dynamic hourly simulation of thermal conditions, air flow, lighting, and radiance surface properties within multizone environments. They provide an early indication of renewable energy contribution, costs, and compliance. They also require significant input data, provide detailed calculations and are generally used during intermediate design stages;

- *Specialist Programs*
  Specialist programs are used for in-depth analysis of: heating, cooling, hot water, lighting, ventilation, acoustics, mechanical and electrical systems, cost, and compliance. They provide detailed guidance for system selection, plant sizing, and component selection. Programs use finite difference, finite element, and state space techniques which require high granularity input data and are used at the detailed design stage;

- *Integrated Programs*
  Integrated programs are used for a holistic approach to design and analysis, and include a selection of features from the other categories.
  And when categorized by *function*, again, four categories appear:

- *Whole Building Analysis*
  This category constitutes a major proportion of simulation programs, each have differing capabilities when addressing: energy simulation, load calculation, renewable energy, retrofit analysis, and sustainability. They are composed of a *core program* to construct the building model, and several *subprograms* that analyze: thermal performance, airflow, lighting, mechanical and electrical systems, radiant surface properties, costing, environmental performance, and compliance;

- *Materials, Components, Equipment, and Systems*
  Programs in this area tend to be specialized, and assess: envelope systems, HVAC equipment and systems, electrical systems, lighting systems, and internal transportation (elevators and escalators);

- *Codes and Compliance*
  Used extensively within industry, programs in this category: ensure designs are compliant with building regulations, look at whole life cycle issues and green assessment methods;

- *Other Applications*
  The sheer complexity of building design requires a suite of specialized supplementary programs that provide analysis of: acoustics, atmospheric pollution, economics, tariff analysis, fire, smoke, evacuation, indoor air quality, thermal bridging, multi-building facilities, solar and climate analysis, training, utility evaluation, validation tools, ventilation and airflow, and water conservation.
  A large engineering consultancy would typically use a selection of programs from each category during a major project, each chosen for a specific function.

Section 12.5.2 details a selection of commonly used programs and compares their different characteristics.

The advance of computing science has enriched the inclusivity of simulation, evidenced by products boasting features which analyze: thermal balance, HVAC systems, HVAC equipment, infiltration, ventilation and multizone airflow, moisture, solar shading, sun paths, renewable energy, electrical systems, environmental emissions, compliance, economic evaluation, and generate summary reports. In addition, programs with online connectivity empower the user further still (Augenbroe 2002), providing them with extended features such as: links to other programs, smart help guides, online technical support, training, user communities, and more. The majority of building simulation tools operate under an annual license subscription, however there are a select few that are distributed under a GPL license, where they are often free to download from the internet.

## 12.2 Historical Development of Building Simulation Tools

Since the 1960s, the building simulation software market has been inundated with hundreds of products. Early programs were initially developed for specific functions, either to investigate HVAC systems or heat balances within single zones for example. Many were *static* programs, only capable of simulating single events. During the late 1960s and throughout the 1970s much work focused on developing techniques and coding to provide enhanced capabilities. Methods such as the transfer function technique (Mitalas and Stephenson 1967), degree days, full load hour, and the bin method (ASHRAE 1997) were continually improved upon. However, advance of computing technology during the 1990s gave way to computationally efficient *dynamic* programs. These functioned with enhanced weather databases and used elaborate algorithms which could be stably encoded within programming scripts. This much awaited development allowed practitioners to simulate multiple events, (hourly calculations) in a single simulation-run and conduct effective seasonal analysis. As previously alluded to, further developments materialized through the introduction of easy-to-use *Graphical User Interfaces* (GUIs). These arguably revolutionized the practice of building simulation by making tasks more intuitive. From this point forward, software development companies appeared to focus on inclusivity and capability. Early programs focused on single system simulation, however nowadays, full programs comprise of a suite of integrated tools which allow users to conduct ‘whole building’ dynamic simulations. For further reading, Sowell and Hittle (1995) provide an evolutionary account of energy simulation methodology.

## 12.3 Building Simulation in the Construction Process

This section takes a look at the role of building simulation tools in the construction process and discusses the range of benefits it offers to different user groups. The latter half of the section considers the uncertainty within simulation results and deals with the issue of interpretation and context.

### *12.3.1 Benefits of Simulation*

#### ***Strategic Design Concepts***

An *initial* design concept is generally simulated using a *simple* simulation program. In few instances, advanced programs are used if there is an integral architectural feature. The architect can quickly gauge whether a design has the potential to deliver the required performance and work through several iterations if necessary. Computational efficiency renders it possible to test a variety of options without jeopardizing project timescales. This is vital, as key design decisions are frequently made in the early stages of a project. Moreover, early simulations allow designers to grasp the range of implications of a design decision through a transparent process which enables them to observe the individual contribution of different physical processes that occur. New concepts, construction materials, construction methods, and even philosophies emerge, as technology advances and society evolves. Building simulation provides an environment to experiment with the new, to see what can be achieved, fosters creativity, and accelerates innovation. Likewise, simulation enhances communication across the design team, reducing the possibility of misinterpretation.

#### ***Sustainable Design***

Sustainability, sustainable architecture, and energy efficiency are themes which are rarely out of modern day headlines. From the early eco-buildings in the 1990s, to the cutting-edge high performance designs of today, the construction industry is witnessing a transformation in the way we shape our urban environment and relate to buildings. Simulation tools are at the epicenter of this design revolution. Internationally, there are eight recognized sustainable building assessment methods: BREEAM (BRE 2009); LEED (USGBC 2010); HQE (ASSOHQE 2010); CASBEE (JaGBC 2011); Greenstar (GBCA 2012); GRIHA (TERI 2012) and DGNB (GeSBC 2012). Simulation tools have had to evolve with these methods, assisting in the analysis of renewable energy technology, CHP, fuel cells, green roofs, and low energy heating, cooling, and lighting systems. The preferable inclusion of passive design techniques and energy optimization has also shaped the way we use simulation tools. Comprehensive means of assessing solar gains, advanced control strategies, thermal mass, natural lighting strategies, and cost comparisons with traditional systems have become a mainstay for contemporary simulation programs. Finally, it is worth noting that the concept of ‘carbon lock in’ is prevalent throughout architecture and designers must be aware and manage the associated risks through robust analysis using building simulation.

#### *Life Cycle Cost*

In parallel with sustainable design, life cycle cost analysts aim to reduce the associated costs of a building over its life time. Capital investment, operational, maintenance, and decommissioning costs are of keen consideration. Simulation enables designers to optimize a building’s geometry, envelope, internal fabric, plant size, and operational strategy in order to reduce these costs. The creation of environments which promote health and wellbeing are likely to bolster commercial productivity, inducing an indirect cost impact, which must not be overlooked.

#### *Financial Risk*

Project overspend becomes a sensitive issue when the unexpected occurs. The holistic capabilities of simulation tools significantly reduce the probability of undesirable situations occurring, and in the world of construction, there are many. When all stakeholders fully appreciate how a building will perform under a range of circumstances, from changes in space use, to final assessment, to handover, the opportunity for project success increases exponentially.

### 12.3.2 Users of Building Simulation Tools

Demand for building simulation tools has been driven by urbanization and construction booms in recent decades as well as the cost-effective growth of computer industry. In 1997, a building energy software directory (Natural Resources Canada 1997) listed 109 different products, compared to 406 products listed in a directory in 2011 (DoE 2012). The increased variety of simulation tools has resulted in an extended range of user groups, beyond those of expert users. Many disciplines now engage with tools, increasing communication amongst different project members, and crystallizing the understanding of cross-disciplinary issues. Seven main user groups are identified:

***Architects***

As a primary user group, architects use simulation programs to derive solutions for a range of key issues: from the impact of building form (envelope, geometry, orientation, glazing ratio, thermal mass, esthetics, and spatial configuration) on essential physical processes, to services, to planning aspects. Simulation programs generate interactive three-dimensional models, enabling engineers, clients, and planners to clearly visualize design concepts and interpret them from within their specialist fields.

***Building Service Engineers***

The other primary user group is engineers. They heavily rely upon simulation programs to optimize environmental conditions within buildings. Often in conjunction with architects, engineers assess, and create effective strategies for: building envelopes, mechanical and electrical systems, heating, cooling, ventilation, lighting, water and acoustics, using *advanced*, and *specialist* simulation programs. Such programs help inform engineers, enabling them to confidently select the most appropriate systems and control mechanisms to satisfy performance and cost requirements.

***Clients***

Clients are generally secondary users of simulation tools. Programs provide the extremely useful function of displaying information in a visual format which can be understood by non-technical audiences. Before a single brick is laid, clients can take a virtual tour of their 'completed' building and 'wonder' around a fully rendered simulated environment (Fig. 12.1), inspect certain building elements and can make esthetic judgments based on animated sequences. This is a particularly powerful feature of simulation programs.

***Local Authority Planners***

For similar reasons to the client, planners can accurately gauge how a scheme could impact on the existing landscape and assess how it could potentially alter the visual character of an environment. Simulation programs can generate highly detailed *visuals*; these drawings depict the proposed scheme, settled within the existing landscape. This is achieved by superimposing a drawing onto landscape photography (Fig. 12.2) or including immediate landscape features in the model itself.

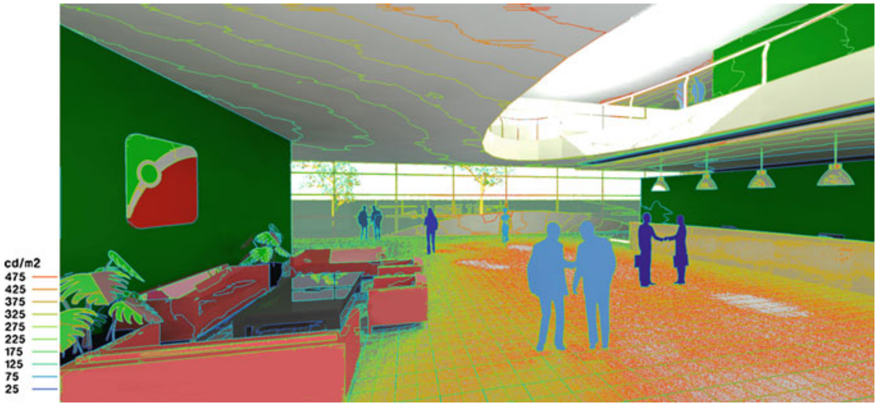



**Fig. 12.1** Rendered visual in IES < VE > Reception Light Level (*Source* Integrated Environmental Solution Ltd, Glasgow)

**Fig. 12.2** Computer visual: the shard, London pre-construction (*source* Hayes Davidson and John Maclean)

### *Cost Planners*

Cost planners are responsible for determining whether a design scheme is financially viable. They work closely with engineers and commonly use specialized programs to analyze the construction, operational, maintenance, and dismantling costs of a building. Building simulation allows cost planners to accurately assign a monetary value to each aspect and ultimately calculate a sale or rental price in the initial stages of a project.

***Project Managers***

Construction projects are notorious for overspend. Project managers are continually required to make judgments and decisions in order to overcome a range of problems in order to delivering projects on time, within budget, and to specified quality criteria. Specialist simulation programs enable this user group to introduce time factors to the various project phases which maximizes labor, space, equipment, and material resources.

***Academics***

Building simulation is a research field in its own right with a dedicated journal (Building Simulation). There is also an extensive body of literature devoted to reviewing, comparing, and contrasting the capabilities of simulation programs (Crawley et al. 2008).

### *12.3.3 Simulation in the Construction Process*

Morbitzer (2003) identifies the three design stages of the RIBA plan of work (RIBA 2008) where there is a heavy reliance on building simulation. This section comments on the various program capabilities which are most appropriate to each work stage.

***Stage C: Design Concept***

The concept design stage aims to provide the client with an appraisal and recommendation to ensure the project is technically and financially feasibility. Simple simulation tools are used to develop a range of outline design proposals and cost estimates requiring timely client feedback. Advanced tools are occasionally used to verify uncompromised design elements.

***Stage D: Design Development***

Design development establishes the general approach to the layout, design, and construction for client approval. The project brief is fully developed, engineers begin to prepare preliminary designs and a cost plan is created. Advanced and integrated simulation tools are generally used to help prepare a full report (Stage D report) and planning application documents.

***Stage E: Technical Design***

All provisions and approvals for planning, appearance, construction method, outline specification, and cost of the project are worked out. Final proposals are developed and detailed design of building components and elements are identified. Building performance is monitored against key performance indicators and cost checking is conducted. Specialized and integrated simulation programs are used to facilitate the majority of tasks here.

Proceeding stages within the RIBA work plan require summary information generated from building simulation during these stages, but do not form the core activity.

## 12.4 Simulation Certainty

Simulating reality is hugely challenging. Some would say impossible. Hong et al. (2000) describe that 'real world' processes must be converted to a 'physical world', then, converted to a 'mathematical world', before finally ending up in a 'computer world'. Converting physical processes from different 'worlds' relies on assumptions, simplifications, and approximations. These, together with anomalies within the construction process and occupant behavior, limit the validity of simulation results. For example, building systems fail to perform to manufacturer specifications, construction materials perform non-uniformly, build quality is variable and occupant behavior can vary energy consumption of similar buildings by a factor of three (Lutzenhiser 1987). Users must therefore interpret their findings with an appreciation of how real-world issues are reflected in simulation results and use experience to gauge whether results appear sensible. Different simulation programs can produce dissimilar results—this is to be expected. Figure 12.3 below, shows the type of algorithms used in simulation programming (Beausoleil-Morrison 2001).

The level of realism a user can achieve is largely dependent on two key factors: first, on the constraints of the software program, and second the skill of the user. Comprehensive software manuals detail a selection of algorithms encrypted in calculation engines, however, nowadays manual calculations are rarely performed as time constraints require building professionals to adopt simulation tools to optimize the execution of complex tasks.

Quality assurance procedures within industry exist to limit risk by standardizing the simulation process to help ensure client requirements are met and value is obtained. Quality assurance standard ISO 9000 (International Standards Organization 1987) is commonly adopted by organizations as a framework to check that:

| Surface | $h_c$ correlation |
|---|---|
| Walls | |
| Assisting forces | $\left(\left\{\left[1.5\left(\frac{\Delta T}{H}\right)^{1/4}\right]^6+[1.23\Delta T^{1/3}]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[-0.199+0.190\times(ac/h)^{0.8}]\right\}^3\right)^{1/3}$ |
| Opposing forces | $\text{Max of}\begin{cases}\left\lvert\left\{\left[1.5\left(\frac{\Delta T}{H}\right)^{1/4}\right]^6+[1.23\Delta T^{1/3}]^6\right\}^{3\cdot 1/6}-\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[-0.199+0.190\times(ac/h)^{0.8}]\right\}^3\right\rvert^{1/3}\\ 80\%\left\{\left[1.5\left(\frac{\Delta T}{H}\right)^{1/4}\right]^6+[1.23\Delta T^{1/3}]^6\right\}^{1/6}\\ 80\%\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[-0.199+0.190\times(ac/h)^{0.8}]\right\}\end{cases}$ |
| Flooor | |
| Buoyant | $\left(\left\{\left[1.4\left(\frac{\Delta T}{D_h}\right)^{1/4}\right]^6+[1.63\Delta T^{1/3}]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[0.159+0.116\times(ac/h)^{0.8}]\right\}^3\right)^{1/3}$ |
| Stably stratified | $\left(\left\{0.6\left(\frac{\Delta T}{D_h^2}\right)^{1/5}\right\}^3+\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[0.159+0.116\times(ac/h)^{0.8}]\right\}^3\right)^{1/3}$ |
| Ceiling | |
| Buoyant | $\left(\left\{\left[1.4\left(\frac{\Delta T}{D_h}\right)^{1/4}\right]^6+[1.63\Delta T^{1/3}]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[-0.166+0.484\times(ac/h)^{0.8}]\right\}^3\right)^{1/3}$ |
| Stably stratified | $\left(\left\{0.6\left(\frac{\Delta T}{D_h^2}\right)^{1/5}\right\}^3+\left\{\left[\frac{T_{surf}-T_{diffuser}}{\Delta T}\right]\times[-0.166+0.484\times(ac/h)^{0.8}]\right\}^3\right)^{1/3}$ |

**Fig. 12.3** An algorithm for calculating convection coefficients for internal building surfaces for the case of mixed flow in rooms (*Source* Beausoleil-Morrison 2001)

simulation results are accurate, work approach is consistent, team coordination is maximized, lessons are learnt, and the overall project aims and objectives are being addressed.

## 12.5 Simulation Programs

The aim of this section is to provide a general understanding of the different characteristics of simulation programs. An exhaustive approach is beyond the scope of this chapter, therefore descriptions have been generalized and individual cases may vary.

### *12.5.1 Program Selection*

Each building simulation program has a particular function, architecture, and overall characteristic. Hong et al. (2000) identify three vital factors for program selection: (1) need or purpose; (2) budget; and (3) availability of facilities. To expand on these points, the selection process must address the following questions:

- What is the final objective?
- What level of certainty is required?
- What input data is available?
- What are the time limitations?
- What are the associated risks?

- Can one program achieve multiple aims sufficiently?
- What is the preferred operating platform?
- What level of user support is required?

As a rule of thumb: simple programs are more suited for concept design, require less input data, and are effective for optimizing overall form, lighting, orientation, and provide an early indication of cost and environmental performance. Whereas advanced and integrated programs require significantly more input data and are appropriate for detailed design to cement core decisions that require accurate calculations.

## 12.5.2 Program Characteristics

The overall characteristic of a program is a product of its capability and usability, shaped by its format, underlying calculation methods, processes, and interface. Table 12.1 features a selection of programs by type, detailing various calculation methods, constituent subdomains, input data requirement, typical applications, and software titles. This is intended to show the variety of program characteristics and illustrate the breadth of issues covered by simulation tools and the level of detail contained within input data.

An example of a graphical user interface can be seen in Fig. 12.4, this is from the lighting program DIAL Europe, a European integrated daylighting design tool (DIAL Europe).

It can be seen that all programs provide an environment to construct the physical model of a building, usually the core module, in which relevant properties can then be assigned to various elements. Depending on program capability, one core module will invariably coexist alongside numerous supplementary modules which allow users to analyze associated subsystems.

For a comprehensive directory of building simulation programs, see the US Department of Energy's online 'Building Energy Software Tools Directory' (DoE 2011).

### Software Compatibility

Compatibility issues can significantly influence data input time. Many simulation programs are designed with compatibility in mind, accommodating popular programs such as *Google Sketchup*, *Auto CAD* and *Revit*, as well as different file types. For example, a digital plan of a building stored on a 'DXF' or 'gbXML' file type, can be directly imported into another program, removing the need for redrawing which can be extremely time-consuming.

**Table 12.1** Selection of programs detailing calculation methods, constituent sub-domains, input data, applications and example software titles

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| Whole building simulation | Core program<br>Subprograms—includes a selection of program types featured below | Building geometry<br>Construction materials<br>Others 'program types' featured below | Roof, external walls, internal partitions, ground contact, doors, internal ceilings, external windows<br>internal windows, roof lights, furniture, surrounding elements<br>Material type, thickness, conductivity, density, specific heat capacity, resistance, vapor resistivity, U-value, inside surface resistance, outside surface resistance, thermal capacity | Specify the building form<br>Specify material properties | BSim<br>DeST<br>DesignBuilder<br>DOE-2<br>ECOTECT<br>Energy Plus<br>Energy-10<br>ENER-WIN<br>eQUEST<br>ESP-r<br>HEED<br>IES < VE><br>TRANSOL |
| Thermal performance | Design chart<br>Elemental<br>Steady state heat loss<br>Quasi dynamic analysis<br>Dynamic analysis | Building model Conditions<br>Systems<br>Internal gains<br>Air exchanges | Geometry and constructions<br>Room type, NCM building type, heating profile, simulation heating set point, DHW consumption, cooling profile, simulation cooling set point, plant (auxiliary energy), solar reflected fraction, furniture mass factor, humidity control (min and max saturation percentage)<br>Space heating (SH): | | |

(continued)

**Table 12.1** (continued)

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| | | | Plant radiant fraction, fuel, seasonal efficiency, delivery efficiency, ScoP, generator size, heat recovery effectiveness, heat recovery return air temperature, CHP | | |
| | | | Space cooling (SC): | | |
| | | | Plant radiant fraction, cooling ventilation, mechanism, fuel, nominal EER, seasonal EER, delivery efficiency, SSEER, absorption chiller, operation, pump, and fan power | | |
| | | | Domestic hot water (DHW): | | |
| | | | DHW delivery efficiency, cold water inlet temperature, hot water supply temperature, storage volume, circulation losses, loop length, pump power | | |
| | | | Solar water heating (SHW): | | |
| | | | Area, azimuth, tilt, shading factor, degradation factor, conversion efficiency, first order heat loss coefficient, second order heat loss coefficient, flow rate, pump power, heat exchange effectiveness, storage tank volume, storage loss at max temp | | |

(continued)

**Table 12.1** (continued)

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| | | | Auxiliary energy and air supply conditions are also specified here<br>Gain type:<br>Fluorescent lighting, tungsten lighting, machinery, miscellaneous, cooking, computers, people<br>Associated parameters can also be specified:<br>Maximum sensible gain, maximum power, consumption, diversity factor, radiant fraction, fuel, variation profile, dimming profile<br>Infiltration, natural ventilation, auxiliary ventilation, variation profile, adjacent condition<br>Infiltration, natural ventilation, auxiliary ventilation | Optimizing the building envelope design<br>Calculate building loads<br>Assess overheating risk<br>Compare different plant technologies<br>Verify compliance | Apache<br>TAS<br>AWDABPT<br>ISE<br>DeST<br>SolArch |

(continued)

**Table 12.1** (continued)

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| DLighting | Artificial lighting:<br>Lumen average<br>Point by point<br>Full lighting simulation<br>Daylighting:<br>Average daylight factor<br>Graphical methods<br>Daylight distribution<br>Physical modelling<br>Full lighting simulation | Building model<br>General properties<br>Luminaires<br>(bulb types) | Geometry and surface properties<br>Illuminance level (lux), lighting glare index, working surface height, mounting height, luminaire maintenance factor, room surface maintenance factor, lamp lumen maintenance factor, replacement period, lamp survival factor<br>Luminaire type, lamp type, lamp color | Develop lighting strategies<br>Minimise luminaires<br>Maximise daylighting<br>Identify luminaire composition<br>Estimate lighting energy: consumption, emissions and cost<br>Verify compliance | FlucsPro<br>Radiance<br>ADELINE<br>DAYSIM<br>Daylight<br>DIALux<br>Eco Lumen<br>FLUCS |
| Air flow | Average infiltration rates<br>Simple theoretical method<br>Flowpaths and networks<br>Computational fluid dynamics (CFD)<br>Physical modeling | Building model<br>Building element<br>Expose type<br>Opening type | Geometry, construction, surface properties<br>Openable are, equivalent orifice area, crack flow coefficient, crack length, turbulence<br>Internal surface, exposed wall, semi-exposed wall, sheltered wall, exposed roof, semi-exposed roof, sheltered roof, low rise building, medium rise building, high rise building<br>Window: side hung, center hung, top hung, bottom hung, parallel hung windows, sash, sliding, louvre, grille, duct, acoustic duct | Develop ventilation strategies<br>Evaluate impact of building form<br>Identify criteria for system selection tools<br>Verify compliance | BUS ++<br>Macroflow<br>FLOVENT<br>IAQ-Tools<br>STREAM<br>COMIS<br>CONTAM |

(continued)

**Table 12.1** (continued)

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| Renewable energy | CFD<br>Generic algorithms | Building model<br>Wind<br>Solar PV<br>Heat pumps<br>CHP<br>Biomass | Geometry and construction<br>Location, hub-height, turbine model,<br>Site, PV array area, tilt, orientation, grid connected, stand alone, configuration, and tracking | Calculating energy contribution<br>Planning permission<br>Aesthetic impact<br>Additional loads<br>Cost, emissions and risk | PVSyst<br>FRESA<br>PV SOL<br>RETScreen<br>TRNSYS |
| Sustainability | ISO 14040<br>NRE<br>CED<br>GWP<br>UBP′06 | Building model<br>Emissions<br>Water<br>LCA<br>Embodied energy<br>Waste<br>Occupant health | Geometry and construction<br>Building models, systems, energy generation, global warming potential, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water use, air pollutants, human health, smog, ozone depletion, toxicity, initial cost, future cost, score [Y] | Assess building impact: emissions, embodied energy, water, waste<br>Life cycle analysis<br>Cost | Athena model<br>Envest<br>GaBi4<br>REEP<br>BEES<br>ECO-BAT |
| Mechanical transportation | Generic algorithms | Building model<br>Elevators<br>Escalators | Geometry and construction<br>Floor names, levels, heights, occupancy number, number of elevator cars, capacity, door times, speed, acceleration, jerk, start delay, shutdown times, restart times, car area, express zone, floors served, handling capacity, step duration, step height, loading time, unloading time, passenger mass, stair factor, and capacity factor | Assess lift and escalator requirement<br>System design<br>Verify compliance | ELEVATE |

(continued)

**Table 12.1** (continued)

| Program type | Methods | Subdomains | Input data | Applications | Software titles |
|---|---|---|---|---|---|
| Acoustics | Quick estimate<br>Global estimate<br>EN ISO 140 | Building model<br>Materials<br>Simulation | Geometry and construction<br>Surface material properties<br>Scattering coefficients, point source, receiver location, number of rays, impulse response length, transition order, late reflection density, key diffraction frequency, and interior margin | Conduct acoustic analysis<br>Evaluate impact of building form and construction materials<br>Predict noise levels<br>Transmission and absorption issues<br>Audio equipment specification and setup | ODEON<br>BASTIAN<br>01 dB<br>PULSE Reflex<br>DIRAC |
| Compliance | EN ISO 14040<br>UK NCM | Building model<br>Materials<br>Building systems | Geometry and construction<br>Construction materials, systems<br>Heating, cooling, DHW, lighting, HVAC, and associated parameters | Check if designs comply with legal standards<br>Predict cost and environmental performance for certification | Climawin<br>COMcheck<br>SBEM<br>SAP calculator<br>ABACODE<br>DIN V 18599 |
| Economics | Life cycle cost<br>Earned value analysis<br>Savings to investment ratio<br>Payback<br>Rate of return<br>Residual value | Energy analysis<br>Energy performance contracts<br>Private sector<br>Public sector | Discount rate, initial investment, interest rate, cash flow requirement, operation maintenance and repair (OMR), loan type, life on loan, points paid, payments, depreciation factor, acceleration rate, salvage value, tax rates, property rates, capital gains adjustment factor, electricity cost, project life | Tariff setting<br>Energy procurement<br>Renewable energy cost adjustments<br>Economic optimization through design<br>stakeholder valuation | AUDIT<br>BLCC<br>Discount<br>EA-QUIP |

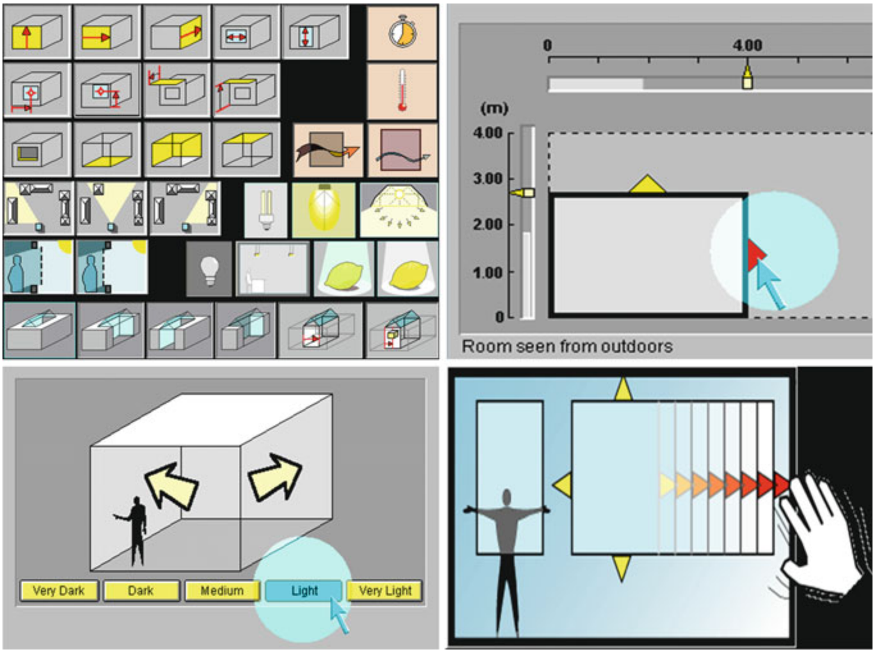



**Fig. 12.4** Graphical user interface for lighting program DIAL

### *Data Inputting*

Most modern programs use a GUI for users to input data, as opposed to a command line or menu driven interface. Again, this significantly reduces the input time and creates an intuitive user experience. Users can systematically navigate around a windows environment, completing data fields either by keying in values or by using drop-down menus and check boxes. Data can also be inputted in some instances using a 'click and drag' or 'drag and drop' functionality, often used when specifying building geometry, adjusting curves on graphs, or moving pointers on 'slide bars'. A programming script operates behind the GUI and inserts numerical values into the corresponding command lines as the user completes the required fields.

### *Databases*

Databases can be applied to many data inputting situations where users need to specify generic physical properties or processes—this considerably increases data input efficiency. For instance, when specifying the properties of six construction materials that comprise a common external wall type, a database could allow users to simply select the precise wall construction system from a choice of ten other popular wall construction systems. Databases are used extensively for: simulating weather conditions, solar irradiance and sun-paths, describing user profiles, specifying materials, products and surface properties, and rendering models.

### *Templates*

Templates are a convenient way of inputting data on mass. They can often include preassigned values that can be edited, such as the type of internal gains for office environments or air flow characteristics for openings in a domestic building. Users can also design customized templates by specifying their own values, and then assign them to various physical systems or processes. For example, a user could create a 'construction materials template' for a type of hospital room (which specifies the material type, thickness, conductivity, specific heat capacity and U-for the ceiling, walls, and floor) and then assign it to 57 rooms on the fifth floor—labor saving!

### *Profiles*

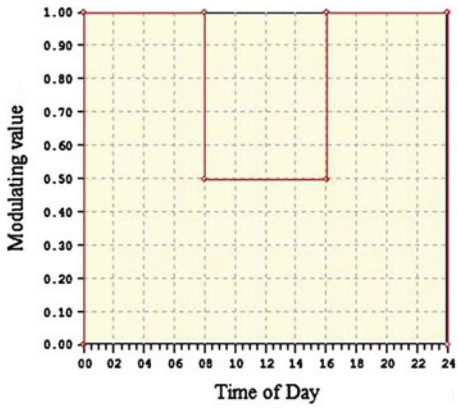
A *profile* describes how a system changes over time. In theory, this might reflect demand intensity, control schedules, occupancy patterns, and behavior. In practice this translates to phenomena such as systems switching on and off, occupants being in or out, or whether windows are open or closed. Simulation programs allow users to construct daily, weekly, monthly, and annual profiles. Figure 12.5 shows a *weekday* heating load profile that could be assigned to a boiler for instance. A database of archetypal profiles are sometimes available for users to assign to various systems, the 'nine to five' office occupancy profile is a commonly featured for instance. As one might expect, profiles hugely improve the predictive performance of simulations and also provide a means for comparing energy reduction scenarios based on control strategies and occupant behavior adaptation, against a reference case.

### *Geography*

The geographical characteristics of a site, its location, and the building orientation all significantly influence overall energy consumption. Immediate shading from nearby objects, micro and macro climates and elevation direction, heavily influences its thermal performance, solar gains, airflow characteristics, renewable energy contribution, and other physical systems. Simulation programs allow users to specify a site's location and its characteristics and optimize its orientation.

### *Data Output*

Essentially, the output of a program is the result of an analysis in some form (simulation results). This is communicated using various methods including




(a)

| | Time | Value |
|---|---|---|
| 1 | 00:00 | 0.00 |
| 2 | 00:00 | 1.00 |
| 3 | 08:00 | 1.00 |
| 4 | 08:00 | 0.50 |
| 5 | 16:00 | 0.50 |
| 6 | 16:00 | 1.00 |
| 7 | 24:00 | 1.00 |
| 8 | 24:00 | 0.00 |

(b)

**Fig. 12.5** Weekday domestic heating load profile: **a** Graphical view, **b** Tabulated view

summary reports, tables or graphical representations (charts, diagrams, and graphs). Effective programs use a combination of formats, pertinent to the subject, enabling users to quickly evaluate their design, identify where improvements can be made, and develop their initial reference case. Non-technical audiences, such as clients and planners, respond well to graphical formats which intuitively communicate information, moreover summary results can be viewed side-by-side to facilitate comparative analysis with relative ease.

***Support***

Newcomers to building simulation are acutely aware of the need for a robust software support mechanism. Likewise, advanced users are similarly frequently faced with new situations and often require resources to obtain solutions. Software support now takes a multitude of formats. Offline, there are: manuals, books, training courses, telephone help desks, and product DVDs. Online, there are: manual downloads, help desks, user communities (forums, blogs, and social media groups), download centers, 'question and answer' pages, case studies, video clips, training, and e-mail requests. Through online enquiry, users nowadays can generally obtain answers to their queries through self-support facilitated by the range of available formats.

## 12.6 Case Study

This case study shows the simple simulation of a new detached home (Fig. 12.6) (Persimmons 2009) using the IES < VE > program. A physical model of the

**Fig. 12.6** Building visual

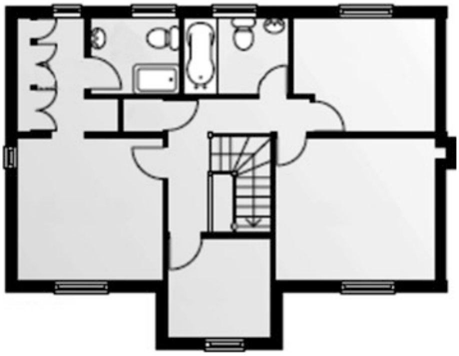


**Fig. 12.7** 1st floor plan

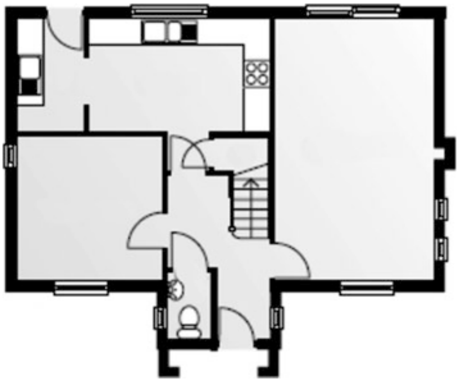
building is initially constructed from floor plans (Figs. 12.7 and 12.8) in the core program (*Model IT*) (Fig. 12.9) which can then be animated for users to observe and verify the geometry (Fig. 12.10).

Construction materials and surface properties are then assigned (Fig. 12.11), together with site data and additional information to specify the correct weather files for simulation. The building's room attributes, thermal and lighting conditions, and air flow characteristics are then specified before a simulation is conducted. Simulation results, detailed in a summary report, showing loads for heating, cooling, lighting, plant, etc., can then be scrutinized before taking further action.

## 12.7 The Future of Building Simulation

At present, thermophysical processes are well represented within the range of simulation tools (Degelman 1999), however the discrepancy between simulated and monitored energy consumption invariably arises due to occupant behavior

Fig. 12.8 Ground floor plan



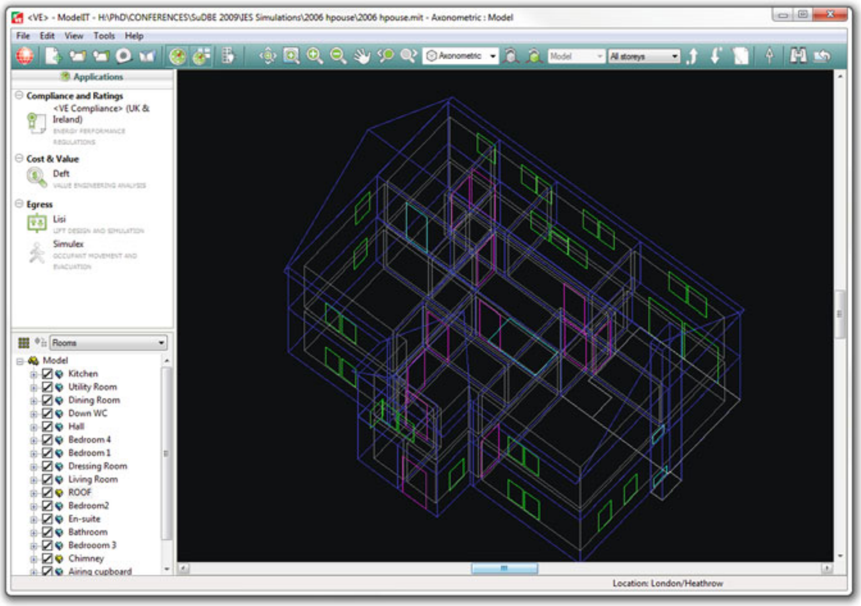



Fig. 12.9 Screenshot of the model geometry in 'Model IT' subprogram

(Shipworth 2010). Much work is currently focussed on bridging this gap (Hoes et al. 2009). Quantifying the impact of occupant behavior and integrating this within simulation tools could result in programs which have:

- Improved control in simulating occupant behavior;
- Provision of databases featuring archetypal occupancy behavior in domestic and commercial environments;
- Means of simulating a greater diversity of behaviors;
- Systems to evaluate the impact of occupancy level and household composition;

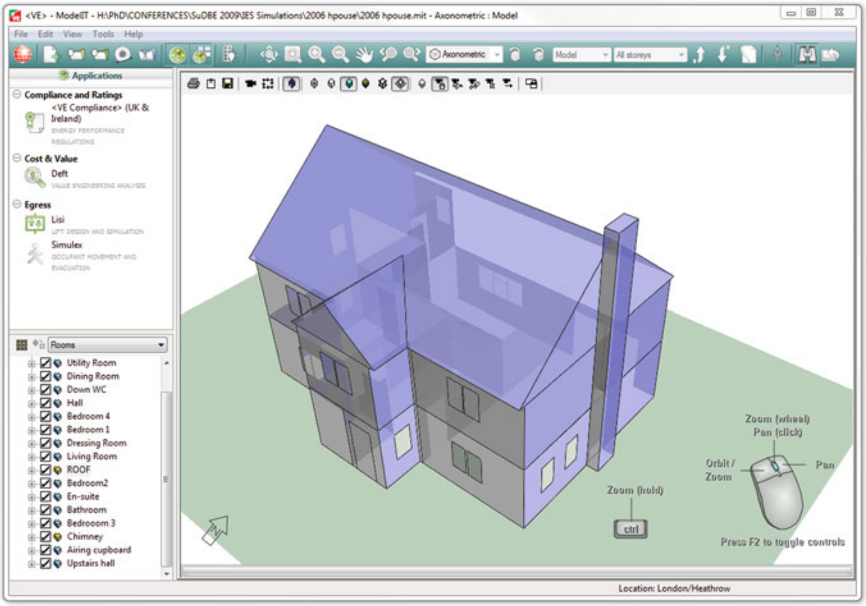



**Fig. 12.10** Screenshot of the model animation in 'Model IT' subprogram

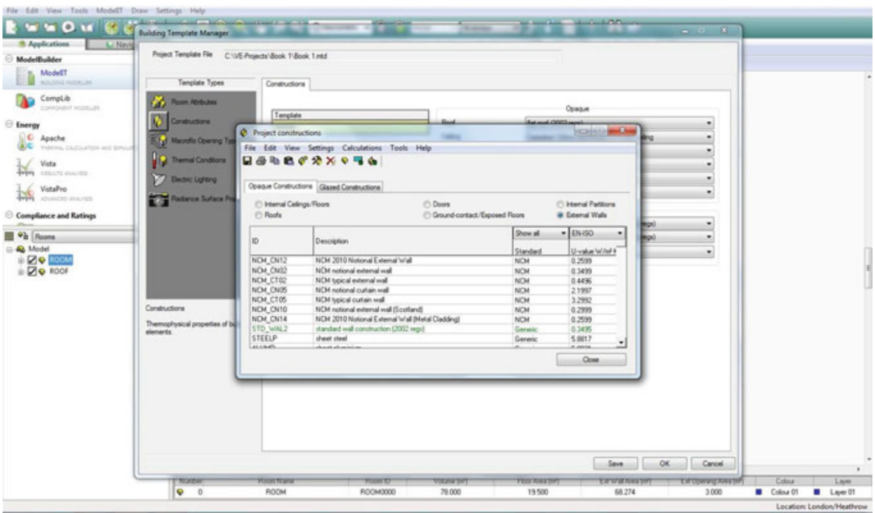


**Fig. 12.11** Screenshot of 'project construction' materials in 'model IT'

- Capabilities to simulating the effects of socioeconomic variables;
- Appreciation of occupant attitudes toward energy use and the environment.

Users could also expect improvements in other areas, including the:

- Improved quality control of simulation results;
- Ability to accurately simulate energy demand of appliances (Lim and Yao 2011);
- Rapid evaluation of alternative designs;
- Artificial intelligence and suggestive functionality;
- Means of assessing the impact of specific energy policies and fuel cost elasticity;
- Increased compatibility across platforms and file type;
- Morphing of weather data files to capture climate change effects (Jentsch et al. 2008).

It is also likely that advances in communication technology could allow users to routinely interact with programs using a three dimensional interface, either on a two dimensional display, similar to 3D television, or the proliferation of holographic technology and virtual reality (Sherman and Craig 2009).
Industry's entrenched need for building simulation will continue. Global attention will remain focussed on the built environment as climate change presents nations with new and unexpected challenges. We will expect more from new buildings in the way of performance and flexibility, and more from existing buildings, post retrofit. Building simulation is a turnkey technology. It enables industry to build with confidence, pioneer new techniques, successfully adapt existing buildings and predict outcomes for our future. Continual advancement in computing science remains as the backdrop for new exciting innovations in building simulation technology; enabling the launch of high performance programs of which we will indirectly benefit from, having visited and lived in the buildings they have once simulated.

## 12.8 Conclusion

As society moves toward a low carbon future, the refurbishment and construction of new buildings becomes increasingly important, not only in mitigating carbon emissions, but in the delivery of environments that foster health and wellbeing. Building simulation is, and will continue, to play a key role in the design, planning, development, and analysis of our built environment. It empowers actors across industry to fulfill their potential, be it architects, engineers, planners, and the like, to deliver high quality buildings that are fit for purpose. Simulation tools are used in nearly every field of construction, with new versions, innovative products, and hybrid programs being continually brought onto the market. Careful selection processes are required to choose the right simulation tool for the right job, as there are over 400 products currently available. The interpretation of simulation results must be viewed in the context of ‘the real world’, with a firm grounding regarding the nature of the input data, as all modeling is only an *approximation* of reality. Nevertheless, simulation tools are becoming ever more intricate, and arguably more accurate, in their interpretation of thermophysical and social processes that occur within buildings. As we look toward the future, technological advancement, coupled with the user’s ability, will undoubtedly provide industry with some powerful tools that will help us deliver innovative, intelligent, user-friendly, and above all, better environments.

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# Chapter 13
# CFD Simulation for Sustainable Building Design

**Guohui Gan**

**Abstract** In this chapter, the computational fluid dynamics (CFD) technique is described for accurate simulation of fluid and heat flow in sustainable technologies and buildings. The technique is demonstrated using three examples; one for each of three different types of flow: (1) *steady state* in wind- and buoyancy-driven natural ventilation; (2) *compressible flow* in a solar-powered ejector for cooling; and (3) *transient state flow* in a horizontal-coupled ground source heat pump for heating/cooling of buildings. When naturally ventilating a building, a double skin façade can enhance the buoyancy effect, but the impact of wind is less certain compared to buoyancy; not only in terms of its unpredictable nature, but also its interactions *with* buoyancy. The performance of a solar-powered ejector is influenced by the nozzle position, and the ideal position for the nozzle outlet is near the diffuser entrance. The heat extraction/injection capacity of a ground-coupled (horizontal) heat exchanger for long-term operation is lower than that used in current design guidance for ground source heat pumps. The technique can also be used for optimization and performance assessment of other technologies and solutions for sustainable building design. *Learning Outcomes*: on successful completion of this chapter, readers will be able to: (1) grasp the underlying principles of CFD and its governing mathematical models and equations, (2) understand the type of applications of CFD and how findings can influence sustainable building design and technology, (3) appreciate the types of conditional requirements that are necessary in order to conduct a simulation, and (4) have a limited knowledge about natural ventilation in offices, ejector refrigeration, and ground source heat pumps (GSHP). This chapter explains the basics of CFD and illustrates its potentials for sustainable building design. The partial differential

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equations for fluid and heat flow and the solution method are introduced, followed by three examples for simulations of natural ventilation, solar cooling, and ground source heating of buildings. Emphasis is placed on the accuracy of simulation from model setup to solution convergence.

**Keywords** Computational fluid dynamics (CFD) • Ejector refrigeration • Ground source heat pump (GSHP) • Natural ventilation • Sustainable building technology

## 13.1 Introduction

Sustainable building design requires consideration of all aspects encompassing energy and resources, from site selection, planning, material sourcing, construction, and operation, to user behavior, and exploiting sustainable solutions such as natural ventilation, solar energy collection, storage, and utilization.

Natural ventilation can be induced by internal buoyancy (using differences of air density) or external wind. The two forces can either assist or oppose each other, depending on the building configuration, wind velocity, and surroundings. The effects of wind and buoyancy on building ventilation can be determined by means of full-scale or reduced-scale measurements or numerical modeling. As one might expect, full-scale measurements are costly and results are site specific, while using reduced-scale models can fail to reproduce realistic conditions for combined wind-driven and buoyancy-driven flow.

By comparison, numerical modeling allows simulation for all types of air and heat flow for full-scale buildings; but accuracy depends on numerous factors including: type of mathematical model, computational domain size, mesh or grid size, time step, boundary conditions, and the degree of convergence. Essentially, computational fluid dynamics (CFD) is a technique for computer simulation of fluid and heat flow using modeling and numerical methods. It has successfully been used for analysis, optimization and design of natural ventilation systems, and naturally ventilated buildings (Allocca et al. 2003; Cook et al. 2003; Gan 2010a) and will be explored further in this chapter.

Solar energy can be harvested directly for passive heating, ventilation cooling, and daylighting of buildings, for heating water (direct use), or powering ejector refrigeration systems. It can also be converted directly into electricity using photovoltaics. Solar energy can be stored in building elements for passive space heating or stored below ground for efficient operation of ground source heat pumps (GSHP). CFD can be used to simulate all these processes of solar-induced fluid and heat flow, such as ventilated cooling of photovoltaics panels (Gan 2009) and building structures (Gan 2011). Other examples involving different types of flow include steady-state compressible fluid flow in a solar-powered ejector and transient state heat flow through a ground-coupled heat exchanger.

An ejector or jet pump is a device that makes use of a high pressure primary fluid to entrain a low pressure secondary fluid to produce a refrigeration effect for the secondary fluid. In an ejector refrigeration system, the ejector replaces the compressor of a conventional vapor compression system. A major advantage of an ejector refrigeration system over a vapor compression system is that operation is possible using low grade thermal energy (e.g., solar energy) instead of electricity. An ejector refrigeration system is also simpler in construction and has fewer moving parts, but is less efficient than a vapor compression system. Design of an ejector is traditionally based on a one-dimensional (1D) analytical solution of equations for compressible flow. The analytical method is, however, not versatile for design optimization and therefore requires a CFD approach (Riffat et al. 1996).

A GSHP is a sustainable technology for heating and cooling buildings. It makes use of earth or ground water as the heat source (or sink) through a heat exchanger. It has lower running costs than a conventional heating and air conditioning system, and is more efficient than an air source heat pump because of the relatively stable temperature of deep soil. However, a GSHP is more expensive to install because it involves a ground-coupled heat exchanger, which consists of underground pipe-work that can either be installed vertically or horizontally. A horizontally coupled GSHP utilizes solar heat stored in the shallow soil and is cheaper. A slight drawback is that it requires more land area to install than a vertical borehole heat exchanger. A horizontal heat exchanger can either consist of straight or coiled (slinky) pipes, and a numerical method can be used to predict its performance.

This chapter involves CFD simulation of fluid and heat flow to facilitate design solutions of sustainable buildings. Its application can predict: (1) wind-driven and buoyancy-driven natural ventilation of a building integrated with photovoltaics; (2) compressible flow of water vapor in a solar-powered ejector for refrigeration; and (3) transient state heat transfer through a horizontally coupled earth heat exchanger for GSHP.

## 13.2 Theory

Simulation of transient fluid and heat flow requires solving governing equations for mass, momentum, and energy conservation. Most fluid flow encountered in the built environment involves different levels of turbulence ranging from microscale to large-scale eddies (swirling effects). Turbulent fluid flow can be solved numerically using: (1) the Reynolds-Averaged Navier–Stokes model (RANS); (2) direct numerical simulation (for all scales of turbulence without using any turbulence model); and (3) a combined solution of the two. From the three approaches, the most practical and commonly used in building design is a two-equation turbulence model (based on RANS). This incorporates the standard $k - \varepsilon$ turbulence model and its variants: the Renormalization Group $k - \varepsilon$ turbulence model (RNG) (Yakhot and Orzsag 1986) and the Realizable $k - \varepsilon$ turbulence model. Here, flow equations using the RNG $k - \varepsilon$ turbulence model are presented because the model can provide better predictions involving buoyancy-driven flow (Gan 1998). The governing equations for non-reactive fluid and heat flow consist of the following equations for mass continuity, momentum, turbulence, and enthalpy.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0 \tag{13.1}$$

where: $\rho$ is the fluid density (kg/m$^3$), $t$ is the time (s), $U_i$ is the velocity component of fluid in $i$ direction (m/s), and $x_i$ is the coordinate.

Momentum equation

$$\begin{aligned} &\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial (\rho U_j U_i)}{\partial x_j} - \frac{\partial}{\partial x_j}\left[\mu_e \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] \\ &= \rho g_i - \frac{\partial}{\partial x_j}\left[\left(P_s + \frac{2}{3}\mu \frac{\partial U_k}{\partial x_k}\right)\delta_{ij}\right] \end{aligned} \tag{13.2}$$

where: $\mu_e$ is the effective viscosity (kg/m-s), $g_i$ is the gravitational acceleration in $i$ direction (m/s$^2$), $P_s$ is the static pressure (Pa), $\mu$ is the laminar viscosity (kg/m-s), and $\delta_{ij}$ is the Kronecker delta ($\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ if $i \neq j$).

The effective viscosity is obtained from

$$d\left(\frac{\rho^2 k}{\sqrt{\varepsilon \mu}}\right) = 1.72 \frac{(\mu_e/\mu)}{\sqrt{(\mu_e/\mu)^3 - 1 + C_v}} d(\mu_e/\mu)$$

where: $k$ is the turbulent kinetic energy (m$^2$/s$^2$), $\varepsilon$ is the dissipation rate of turbulent kinetic energy (m$^2$/s$^3$), and $C_v \approx 100$.

Turbulent kinetic energy

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_i k)}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{\mu_e}{\sigma_k}\frac{\partial k}{\partial x_i}\right) = \mu_t S^2 - \frac{g_i}{\rho}\frac{\mu_t}{\sigma_t}\frac{\partial \rho}{\partial x_i} - \rho\varepsilon\left(1 + 2\frac{k}{c^2}\right) \tag{13.3}$$

where: $\sigma_t$ is the turbulent Prandtl number, $\sigma_k$ is the Prandtl number for turbulent kinetic energy, $\mu_t$ is the turbulent viscosity (kg/m-s), S is the modulus of rate of strain tensor $S = \sqrt{1/2\left(\partial U_i/\partial x_j + \partial U_j/\partial x_i\right)\left(\partial U_i/\partial x_j + \partial U_j/\partial x_i\right)}$, $c$ is the speed of sound (m/s), $c = \sqrt{(\gamma \mathrm{RT})}$, $\gamma$ is the specific heat ratio, $R$ is the gas constant (J/kg K), and $T$ is the absolute temperature (K).

Dissipation rate of turbulent kinetic energy

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho U_i \varepsilon)}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{\mu_e}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) = C_1 \mu_t S^2 \frac{\varepsilon}{k} - C_2 \rho \frac{\varepsilon^2}{k} - C_3 \frac{g_i}{\rho}\frac{\mu_t}{\sigma_t}\frac{\partial \rho}{\partial x_i}\frac{\varepsilon}{k} - Sr \tag{13.4}$$

where: $\sigma_\varepsilon$ is the Prandtl number for turbulent dissipation rate, $C_1 = 1.42$, $C_2 = 1.68$, $C_3 = \tanh(U_v/U_h)$ with $U_v$ and $U_h$ being the vertical and horizontal mean velocity components, respectively, and $Sr$ is the rate of strain given by

$$Sr = \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3} \frac{\varepsilon^2}{k}$$

where: $\beta = 0.012$, $\eta_0 = 4.38$, $\eta = \mathrm{S}\ k/\varepsilon$

$\sigma_t$, $\sigma_k$, and $\sigma_\varepsilon$ in Eqs. (13.3) and (13.4) are computed via

$$\left|\frac{\alpha - 1.3929}{\alpha_0 - 1.3929}\right|^{0.6321} \left|\frac{\alpha + 1.3929}{\alpha_0 + 1.3929}\right|^{0.3679} = \frac{\mu}{\mu_e}$$

where: $\alpha_0 = 1/\sigma$ (with $\sigma$ being the laminar Prandtl number) for $\sigma_t = 1/\alpha$ and $\alpha_0 = 1.0$ for $\sigma_k = \sigma_\varepsilon = 1/\alpha$.

Energy equation

$$\begin{aligned} &\frac{\partial(\rho H_i)}{\partial t} + \frac{\partial(\rho U_j H_i)}{\partial x_j} - \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\sigma} + \frac{\mu_t}{\sigma_t}\right)\left(\frac{\partial H_i}{\partial x_j}\right)\right] \\ &= \frac{\partial}{\partial x_j}\left\{U_i \mu_e \left[\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right] - U_j P_s\right\} + q \end{aligned} \tag{13.5}$$

where: $H_i$ is the specific enthalpy in $i$ direction (J/kg) and $q$ is the volumetric heat production/dissipation rate (W/m$^3$).

For pure conduction heat transfer in a stationary (e.g., solid) medium, $U_j = 0$, $H_i = C\ T$, $C\ \mu/\sigma = \lambda$, and $\mu_t = 0$, where $C$ is the specific heat (J/kg K), and $\lambda$ is the thermal conductivity of the medium (W/m K). Hence, Eq. (13.5) reduces to

$$\frac{\partial(\rho C T)}{\partial t} - \frac{\partial}{\partial x_i}\left[\lambda\left(\frac{\partial T}{\partial x_i}\right)\right] = q \tag{13.6}$$

All the thermal properties and the density of a solid medium can vary with temperature, location, and time as well as constituents of a porous medium such as the moisture content of soil. The density of fluid is related to the absolute pressure $P$ (in Pa) and temperature T according to the following ideal gas law

$$\rho = \frac{P}{RT} \tag{13.7}$$

Equations (13.1) to (13.6) can be generalized in the following form:

$$\frac{\partial(\rho\varphi)}{\partial t} + \frac{\partial(\rho U_i \varphi)}{\partial x_i} - \frac{\partial}{\partial x_i}\left[\Gamma_\varphi\left(\frac{\partial\varphi}{\partial x_i}\right)\right] = S_\varphi \tag{13.8}$$

The first term on the left hand side represents the variation of flow variable $\varphi$ with time, the second term represents the flow by convection, and the third term represents the flow by diffusion (with diffusion coefficient $\Gamma_\varphi$) or heat transfer in a solid medium by conduction (diffusion coefficient $\Gamma_\varphi$ = thermal conductivity $\lambda$). The term on the right represents the source or sink of the flow.

The partial differential equations for fluid and heat flow are commonly solved using the control volume method, together with an algorithm to link the velocity with the pressure which is implicit in the continuity and momentum equations. In the control volume method, a flow geometry or computational domain is decomposed into a finite number of control volumes or cells. A partial differential equation is first integrated over each of the control volumes and the integral equation is then descretized into an algebraic equation at all the nodes (a node being a point at the center of a control volume). Finally, a set of algebraic equations are solved numerically for given initial and boundary conditions. The process of numerical solution involves iteration (updating flow variables repeatedly), until the residual for each flow variable is less than a prescribed small value and the variations in both the residual and flow variable between iterations become negligible. Due to the nonlinear nature of the flow equations, to achieve a converged solution requires the use of such measures as: (1) under relaxation to limit the update of a flow variable; (2) disabling the turbulence model or viscous model altogether at the beginning for compressible flow modeling; and (3) reducing time steps for transient state flow modeling at times when rapid flow changes take place, which is also necessary for accurate simulation.

Validation of the CFD technique has been carried out for buoyancy-driven air flow in vertical cavities (Gan 2010b, 2011) and heat transfer for a ground-coupled heat exchanger (Wu et al. 2010). In the following three sections, CFD is applied to simulations of incompressible flow in natural ventilation of buildings and compressible flow in a solar-powered ejector for air conditioning using commercial CFD software (FLUENT 2005) and simulation of transient state heat transfer in a horizontally coupled earth heat exchanger system for GSHP using an in-house computer program.

## 13.3 Simulation of Natural Ventilation of Buildings

CFD is used to simulate a naturally ventilated office building (with façade integrated photovoltaics) with steady-state air flow and temperature distribution. Figure 13.1 shows the schematic diagram of the building (cross section).

The width of the building is large enough to allow simplification as two-dimensional (2D) flow. The building consists of three floors of open plan offices 10 m deep and 3 m high, linked to a south-facing double skin facade with a 0.8 m wide and 12 m high cavity. Photovoltaic modules with a 15 % electric conversion efficiency forms three sections of the external skin at a height of 2.5 m above each floor. They cover approximately one half of the area to allow external views and daylight, while providing dual provision for solar shading and electricity generation. The equivalent opening size of windows is 0.2 m in both the external wall and internal wall. There are also two vertical openings (0.4 m) at the top of the

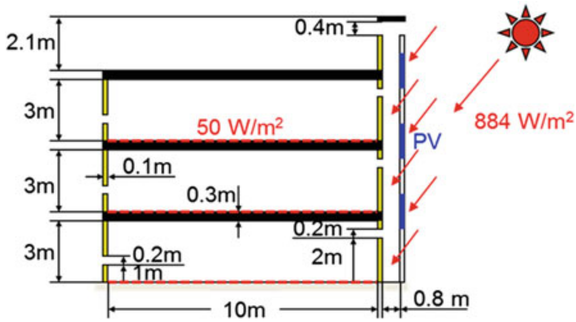


**Fig. 13.1** Schematic diagram of the office building

double facade. Internal heat gains on the floors of offices are assumed to be 50 W/m$^2$. Solar shading elements in the double facade are ignored in the simulation, but solar heat gains on the two facade skins are calculated from solar radiation of 884 W/m$^2$. This solar radiation figure is obtained for summer conditions in the London area on a horizontal plan (CIBSE 2006). Last, the external air temperature for the same period is 22.7 °C.

For simulating the effect of wind, we have to specify the atmospheric boundary layer profile for an urban terrain. This is used to specify the inflow wind velocity with respect to height. The following equation is used:

$$V_z = 0.35z^{0.25} V_{10} \quad (13.9)$$

where $V_z$ (in m/s) is the wind speed at height $z$ (in m) and $V_{10}$ is the wind speed measured at a weather station at 10 m high (CIBSE 2006).

For accurate simulation of both wind-driven and buoyancy-driven natural ventilation, a much larger computational domain than just the physical dimensions of a building is necessary; the computational domain, or domain boundary, being the 'edges' of the simulated space. The distances from the building to the windward (the side which wind is blowing onto), leeward (the side which is sheltered from the wind), and top side (area above the roof) of the domain boundary are at least six, twelve, and six times the building height, respectively (see Fig. 13.2).

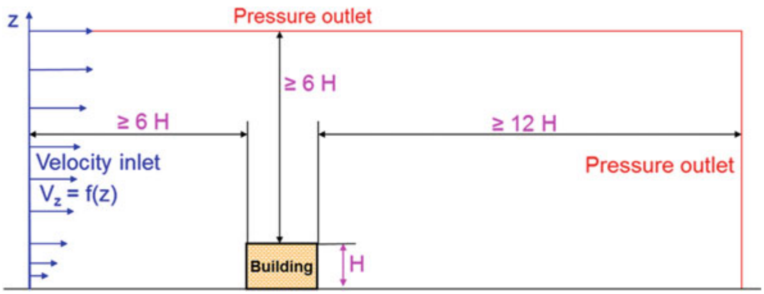


**Fig. 13.2** Computational domain for simulation of natural ventilation of a building with height H

The domain is divided into an unstructured mesh of about one million cells to achieve a ‘mesh-independent solution’ (with fine cells) distributed in and around the building. The ground surface and building structure are defined as fixed walls and the rest of the domain boundary as openings (prescribed with pressures or the wind velocity profile [Eq. 13.9]). Figure 13.2 shows the type of boundary for simulating wind-driven or combined wind- and buoyancy-driven natural ventilation. For simulating natural ventilation due to buoyancy alone, the two vertical edges of the domain boundary are defined as the pressure inlets.

As flow velocity (or wind flow rate) at the boundary for buoyancy-driven natural ventilation is unknown prior to simulation, the flow inside the domain and at the boundary changes simultaneously with iteration (simulation steps). The magnitude of the change reduces as the number of iterations increase as it works slowly toward the converged solution. However, the cumulative variation in flow through a building could be significant. Therefore, the convergence of a solution for flows involving buoyancy needs to be judged from the monitored residual and key parameters, not merely between consecutive iterations but between thousands of iterations.

Simulations are performed for the coupled internal and external environments of the building under buoyancy and wind effects, separately, and in combination. For wind-driven flow simulation, a wind speed of 4 m/s is assumed; this is the annual average wind speed in England at 10 m above ground level. The direction of wind is normal to the building’s front elevation (i.e., from north or south for a south-facing building).

### *13.3.1 Buoyancy-Driven Natural Ventilation*

Figure 13.3 shows the predicted airflow patterns, temperatures, and static pressure distributions in the building under buoyancy-driven natural ventilation. Ambient air is induced into the building from window openings on the external wall and gradually warms as it flows across the floors. This warmer air then moves upward, into the double skin façade, due to buoyancy. Buoyancy effects are greatly enhanced by solar heat gains that raise the air temperature even further, reducing air density; finally the warm air leaves the cavity through the openings near the top of the façade.

Greater air movement is experienced on lower floors than upper floors due to a greater buoyancy effect. This is the characteristic of larger distances between the inlet window and the neutral pressure plane which is the point where internal and external pressures equalize, at a height of 0.7 m above roof level. The air pressure on the ground and first floor is less than the external air. Moreover, air pressures on the top floor are also lower (up to top of the window), but higher than external pressures above that point. Consequently, the ventilation rate on the top floor is much lower compared to the bottom floor; also, there would be no supply of fresh air to this office, from the external window opening, without the enhanced ‘stack

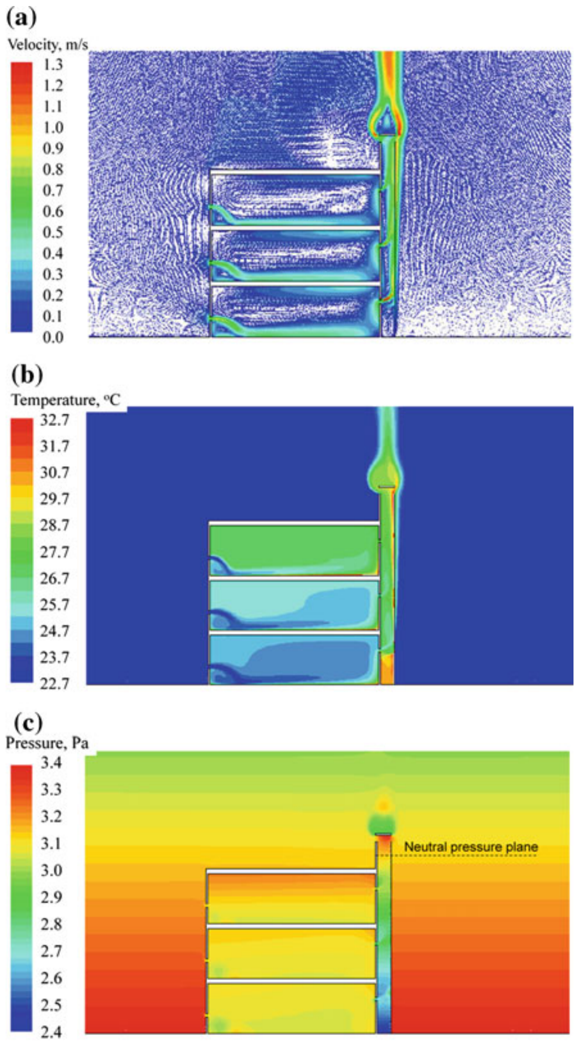


**Fig. 13.3** Predicted airflow patterns, temperature, and pressure distributions in the building with buoyancy-driven natural ventilation **a** Airflow patterns, **b** Temperature distribution, and **c** Pressure distribution

effect' in the double skin façade. Average incoming air velocities vary from 0.74 to 0.42 m/s, from the ground to top floor. Interestingly, air velocities experienced in offices away from windows reach less than 0.5 m/s at floor level and are almost negligible at head height.

The predicted ventilation rates and average air temperatures within the offices are given in Table 13.1. High ventilation rates occur within all the offices, with the minimum value of 8.4 l/s per $m^2$ of floor area, indicated on the top floor (or 84 l/s for an occupant with a 10 $m^2$ floor space). Removal of internal heat gains from all floors is facilitated by the large amount of cool incoming air which would result in 'comfortable' to 'slightly warm' thermal comfort conditions during the summer. The buoyancy effect leads to temperature stratification in each of the offices, and

**Table 13.1** Predicted ventilation rates and temperatures in the offices (from North)

| Floor | Buoyancy only | Wind only (from north) | Wind + buoyancy | |
|---|---|---|---|---|
| | | | Northerly wind | Southerly wind |
| Ventilation rate (L/s per m$^2$ floor area) | | | | |
| Ground | 14.8 | 25.5 | 27.4 | 14.2 |
| First | 12.2 | 31.2 | 29.1 | 10.8 |
| Second | 8.4 | 25.0 | 24.9 | 6.4 |
| Average room temperature ($^{o}$C) | | | | |
| Ground | 24.5 | 23.5 | 23.5 | 25.1 |
| First | 25.1 | 24.4 | 23.4 | 26.0 |
| Second | 26.8 | 23.6 | 23.6 | 29.2 |

between offices; in contrast with decreasing ventilation rate, the average air temperature increases from 24.5 °C for the ground floor to 26.8 °C for the top floor. Due to stratification, temperatures at foot level are more thermally comfortable than at head level. Increasing the openness of the windows on the other hand, would achieve thermal comfort in the offices. Air temperature within the double facade (cavity) rises to an average of 27.5 °C: helpful in one respect for ventilation cooling, but not in another, as cooling loads can increase if heat is not promptly removed and solar shading is absent. Such undesirable effect is experienced toward the bottom of the cavity, where solar heat is trapped below the window opening on the ground floor.

### *13.3.2 Wind-Driven Natural Ventilation*

To observe only wind-driven natural ventilation, buoyancy effects are excluded within the following set of simulations. When wind flows from the north, the overall flow direction is the same as the 'buoyancy simulations' previously conducted. Ambient air flows into the building through external wall openings, passes through the rooms, into the double façade cavity and out through the top (Fig. 13.4). Incoming air flows across the floor on the ground and second floors, but on the first floor air flows upwards along the ceiling. The wind-driven ventilation rates are much higher than buoyancy-driven ventilation by a factor of approximately 0.75, 1.5, and 2 for the ground, first, and second floor, respectively. Wind-driven natural ventilation rates generally increase with the vertical position of opening/floor from the ground because of the increasing wind speed, whereas buoyancy-driven ventilation decreases with the position.

Furthermore, wind-driven ventilation rates for the top floor are lower than those on the first floor because a proportion of the approaching wind flows over the roof, reducing the impact on the facade. Also, because incoming air for the first floor bypasses the uniformly distributed heat source on the floor, air temperature in the room is slightly higher than that in the top floor, in spite of the higher ventilation

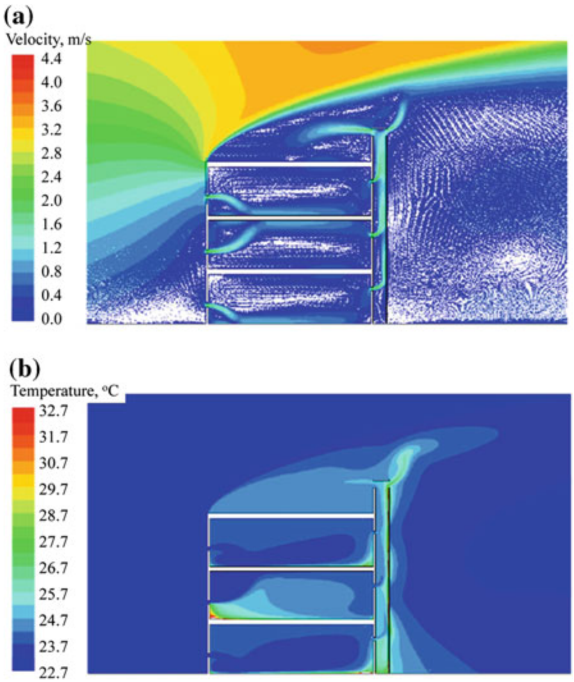


**Fig. 13.4** Predicted airflow patterns and temperature distribution in the building with wind-driven natural ventilation **a** Airflow patterns **b** Temperature distribution

rate. It seems that the average air temperature in all the offices is around 24 °C and, hence, satisfactory for thermal comfort.

To investigate the effect of inflow wind-boundary type, a simulation is also performed using a uniform wind velocity, instead of the wind profile (increasing wind speed with height) as a boundary condition. The uniform velocity is obtained from a reference wind speed at roof height. Results suggest that the effect on the ventilation rate and air temperature is not significant. When comparing wind and buoyancy-driven flows, the maximum difference in ventilation rate for each of the floors is about 7 %, and the difference for the building as a whole, is less than 3 % (comparing Tables 13.1 and 13.2). Average air temperature difference in the offices varies within 1 °C. This suggests that simulation of wind-driven natural ventilation could be simplified using the reference wind speed as the uniform inflow velocity. This is provided that the upstream boundary is sufficiently far away from the building, such that a velocity profile along the vertical direction due to ground friction could be established well before air approaches the building. However, the phenomenon of incoming air flowing along the ceiling instead of the floor would occur in the top floor using the uniform velocity rather than in the first floor. This is consistent with the phenomenon observed in a more complicated building with two wings of offices (Gan 2010b). It is also the main reason for the temperature difference in the top two floors using the two types of inflow velocity because incoming air that flows along the ceiling of an office could not efficiently

**Table 13.2** Predicted ventilation rates and temperatures in the offices using a uniform inflow wind velocity

| Floor | Wind only | | Wind + buoyancy | |
|---|---|---|---|---|
| | Ventilation rate (L/s-m$^2$) | Room temperature (°C) | Ventilation rate (L/s-m$^2$) | Room temperature (°C) |
| Ground | 27.0 | 23.5 | 28.2 | 23.5 |
| First | 30.0 | 24.4 | 30.8 | 23.4 |
| Second | 27.0 | 23.5 | 24.0 | 23.7 |

remove the heat from the floor. If the indoor airflow patterns are the same, similar to the bottom floor, then the average room temperature would hardly be affected by the type of inflow velocity for this building with such a large ventilation rate.

### *13.3.3 Combined Wind-Driven and Buoyancy-Driven Natural Ventilation*

In reality, buoyancy is present whenever there is a heat source/sink in a space. Airflow patterns in and around a building, under both wind and buoyancy forces, are shown in Fig. 13.5a.

The flow patterns under combined wind- and buoyancy-driven natural ventilation are similar to those under buoyancy-driven natural ventilation, with air flowing along all floors. In terms of ventilation rate, however, the combined wind and buoyancy-driven natural ventilation is closer to wind-driven natural ventilation due to the much larger effect of wind than buoyancy. The ventilation rate for the ground floor under the combined wind and buoyancy effects is about 7 % higher than that under the wind effect alone; but the ventilation rate for the first floor is lower by a similar proportion. This indicates that wind force assists the buoyancy effect on the ground floor, but the two forces oppose each other on the first floor: wind drives the air flow along the ceiling and negative buoyancy of cool incoming air flows along the floor, though the overall flow in the horizontal direction is forward from the north to south. Consequently, the total ventilation rate for the building under the combined wind and buoyancy effects is no larger than that under the wind effect alone. Although the ventilation rate is reduced in the first floor, the air temperature is lower than achieved with wind-driven ventilation because of better mixing of incoming air with room air. Also, the combined wind and buoyancy effects lead to similar magnitudes of the ventilation rate and resulting average air temperature in the offices. The average air temperature is about 23.5 °C with a difference of only 0.1 °C, and so the indoor environment would be acceptable for thermal comfort (Fig. 13.5b).

Another simulation of combined wind-driven and buoyancy-driven air flow using a uniform inflow velocity (based on the reference height), results in similar airflow patterns, ventilation rates, and temperature distribution in the offices, to

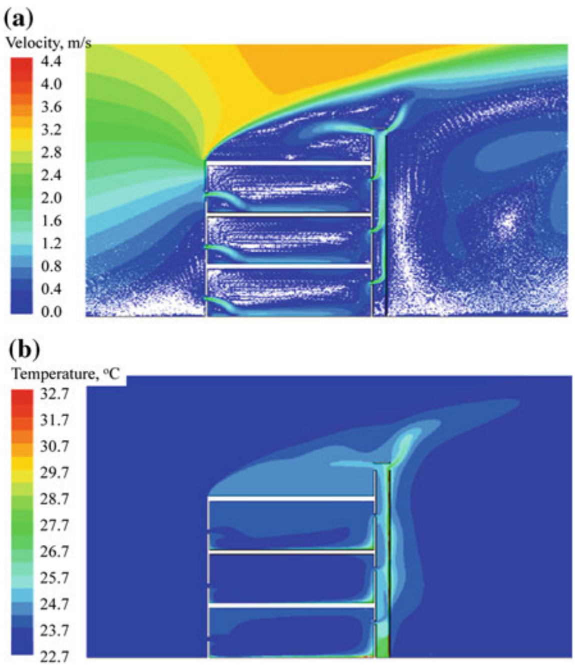


**Fig. 13.5** Predicted airflow patterns and temperature distribution in the building with combined wind- and buoyancy-driven natural ventilation **a** Airflow patterns **b** Temperature distribution

those using the wind profile. Simulation differences from using the two types of inflow velocity shows a decrease of 2 % in ventilation rate, but predicted average temperatures in all of the offices remains about the same. This shows that using a uniform inflow velocity at a far-field boundary is a reasonable simplification for a wind profile when simulating natural ventilation in this case.

When the wind flows from the south, toward the double facade, overall airflow patterns in the building remain the same—cool outdoor air flows into the offices through the external windows and warms indoor air that exits through the internal window openings and then through the double facade. However, the predicted ventilation rates on the ground, middle, and top floor are approximately 4, 12, and 25 %, respectively, less than those under the buoyancy effect alone. As a result, the average air temperature rises by about 1 °C in the lower two floors, still acceptable for thermal comfort, but on the top floor, a rise of 2.5 to 29.2 °C is experienced, which exceeds thermal comfort. Hence, when wind is obstructed by the building structure, its contribution to ventilation becomes less or even negative. In such case, wind becomes an opposing force to buoyancy in the building. The main cause of this adverse effect is the air outlet at the top of the cavity, which forces wind flowing from the windward opening to the leeward opening rather than 'sucking' air from the double skin façade, out of both openings as in the case when wind is from the north; thus effectively reducing the ratio of the total outflow opening area to the total inflow opening area from $2 \times 0.4/(3 \times 0.2) = 1.33$ to $0.4/(0.6 + 0.4) = 0.4$. The adverse effect can be minimized by increasing the (leeward) outflow, reducing or even closing the windward openings, removing the horizontal cover, or changing the cover shape to produce the beneficial effect of wind, functioning as a wind cowl. For example, when the horizontal cover is removed, wind becomes an assisting force to buoyancy and the predicted ventilation rates in the offices are about 5 % higher than those under the buoyancy effect only. In practice, openings can also be provided and operated for each floor in both skins of the double façade (at a height below the photovoltaic modules), to enhance wind-driven natural ventilation when wind flows toward the double facade or in other directions. The full effects of such design and operation can be simulated using CFD.

## 13.4 Simulation of Solar-Powered Ejector Refrigeration

An ejector refrigeration system can be driven by waste heat or solar energy. A solar-powered ejector refrigeration system consists of an ejector, a generator powered by solar thermal, an evaporator, and a condenser. Figure 13.6 shows the solar-powered ejector refrigeration cycle. As heat from the solar collector (which is backed up with a boiler) is added to the primary fluid in the generator, vapor is generated which occurs at high pressure and temperature. Vapor then enters the nozzle of the ejector where it accelerates and discharges at a supersonic speed, into the diffuser, which entrains the secondary fluid from the evaporator into the suction chamber (Fig. 13.7). The primary (motive) and secondary (suction) fluids combine within the diffuser's mixing section and then flow through the diverging section of the diffuser. The mixed fluid decelerates and then discharges to the condenser, where the vapor is condensed into liquid. Most of the liquid returns to the generator via a pump while the rest of the liquid expands through the throttling into the evaporator to complete the cycle. To achieve sufficiently high enough temperatures for the primary fluid in the generator, evacuated tube solar collectors are preferred as opposed to flat plate collectors due to higher efficiencies. A conventional boiler is used as a back-up energy source to ensure security of operation at all times, particularly when solar radiation is insufficient and cooling demands are high.

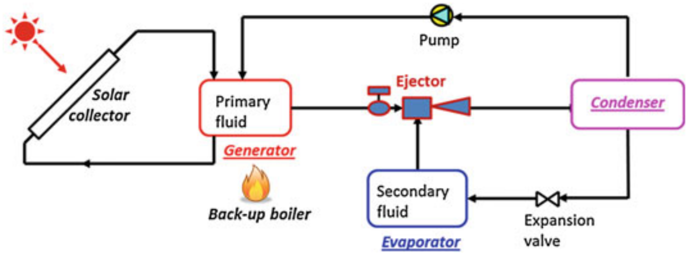


**Fig. 13.6** Schematic diagram of the solar-powered ejector cooling system

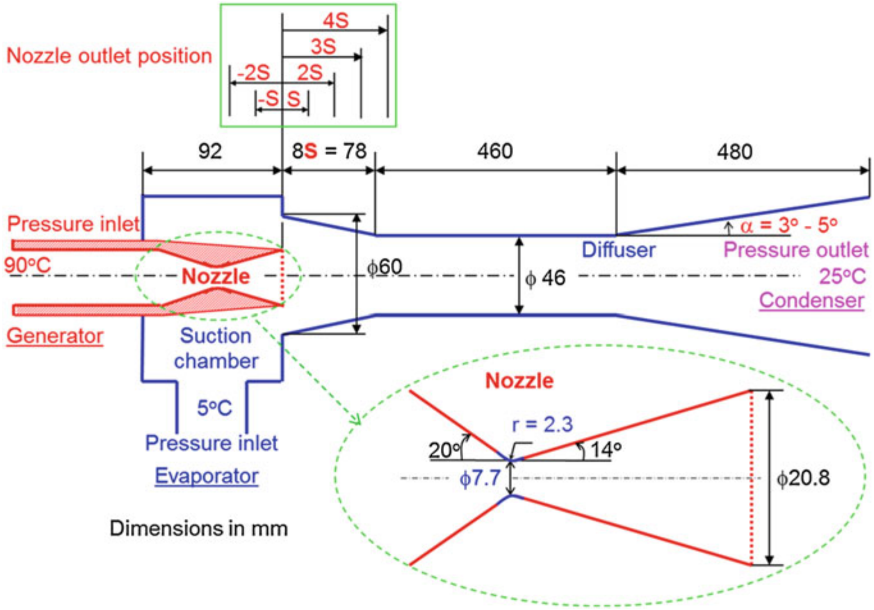


**Fig. 13.7** Dimensions of the ejector for simulation

Specifications and considerations for the ejector simulation are as follows:

- The ejector is about 1 m long, the throat of the nozzle is 7.7 mm in diameter, and the outlet diameter of the nozzle is 20.8 mm;
- The nozzle outlet is aligned with the diffuser inlet for the initial base-case simulation;
- The diffuser consists of a contraction (entrainment section) of 78 mm long, a straight section of 46 mm in diameter, and length being 10 times the diameter which together with the contraction forms the mixing section;
- The expander is 480 mm long and has an expansion angle varying from 3 to 5°;
- Water is used as the working fluid;
- The temperature of water vapor from the generator is 90 °C;
- The evaporator is at 5 °C and the condenser at 25 °C;
- Saturation pressures corresponding to the operating fluid temperatures are used to prescribe the boundary conditions for openings to the generator, evaporator, and condenser;
- The fluid flow in the ejector is compressible due to the large pressure differences between the openings and expected high velocities;
- A 3D unstructured mesh of just over two million cells is used for simulation.

It is more difficult to achieve a converged solution of compressible flow than incompressible flow in terms of convergence speed and due to the solution itself. The residual's variable during iteration may not be a good indicator of convergence for this type of flow, nor for buoyancy-driven flow. The scaled residual for all variables can become small (e.g., $10^{-3}$ or even $10^{-6}$), relatively quick, but the solution may not have reached full convergence according to expected flow rates through the openings. For instance, the flow rate at the opening for the secondary fluid may still be negative (i.e., showing reverse flow) at this stage of solution. Therefore, it is imperative to monitor the flow rates or other parameters representing the compressible flow during iteration. Only when monitored parameters and residuals do not change with further iteration, the solution can be considered fully converged. In order to arrive at this point, it may take more than the usual amount of iterations for the residual to be less than a small value (e.g., 35,000 iterations) for flow rates to be stable in comparison with 3,000 and 6,000 iterations for the residual to drop below $10^{-3}$ and $10^{-6}$, respectively.

Figure 13.8 shows predicted flow patterns of water vapor in the ejector with an expansion angle of 3° for the diffuser. Fluid velocity is extremely high at the nozzle outlet, with a maximum velocity of about 1,000 m/s (four times that of the speed of sound), as shown in Fig. 13.9a showing variations along the axis of the ejector, due to rapid expansion of the high pressure fluid into the low pressure zone. The fluid velocity decreases (along the flow direction) to the sonic speed at about 0.2 m from the nozzle outlet. The high velocity of the primary fluid causes a huge pressure drop such that secondary low pressure fluid is entrained (or 'sucked') from the evaporator into the suction chamber. The two vapor streams then amalgamate in the mixing section and subsequently flow along the diffuser at decreasing velocities, but at increasing pressures (Fig. 13.9b). The fluid's static pressure just beyond the nozzle outlet is very low because it converts to dynamic pressure, which enables the entrainment of the secondary fluid and results in the refrigeration effect.

Figure 13.8 combinedly shows predictions concerning the total temperature of water vapor in the ejector. Hot vapor from the generator mixes with cold vapor from the evaporator in the diffuser. The mixed vapor discharges from the diffuser at about 72 °C and needs cool in the condenser at a temperature of 25 °C.

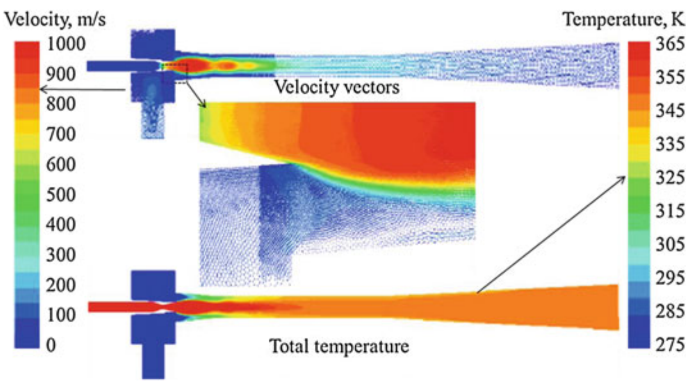


**Fig. 13.8** Predicted flow patterns and temperature distribution of water vapor in the ejector

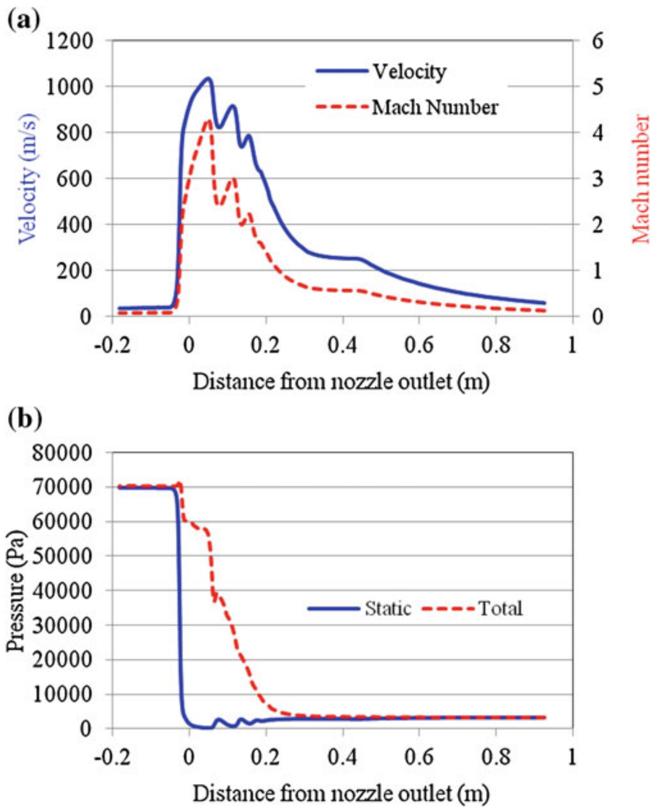


**Fig. 13.9** Variations of velocity and pressure along the ejector axis **a** Velocity and Mach number **b** Pressure

The performance of an ejector is assessed using entrainment ratios and the coefficient of performance (COP); entrainment ratio being the ratio of the mass flow rate of secondary fluid to primary fluid, and COP being directly proportional to the entrainment ratio, such that:

$$\mathrm{COP} \approx \omega \frac{h_e - h_c}{h_g - h_c} \tag{13.10}$$

where: $\omega$ is the entrainment ratio, $h_g$ and $h_e$ are the enthalpies of primary and secondary fluids at the generator and evaporator, respectively, and $h_c$ is the enthalpy of liquid at the condenser (J/kg).

As the enthalpy ratio is less than unity, the COP value is less than the entrainment ratio. The predicted entrainment ratio for this ejector configuration, under given operating conditions, is 0.31 and the value of COP is slightly lower at 0.29.

Further predictions are carried out for different nozzle positions and diffuser expansion angles. To vary nozzle position, it is moved backward or forward so that the outlet is in the suction chamber or in the diffuser by a distance of certain multiples, or a fraction of $S = 78/8 = 9.75$ mm, where $8\,S = 78$ mm is the length of the diffuser contraction.

Figure 13.10 shows predicted variation of the entrainment ratio and COP with nozzle position of the ejector for expansion angles of 3°, 4°, and 5°. Entrainment ratio is greatest where the nozzle outlet is near, or at, the diffuser entrance which is considered the optimum position for ejector efficiency. This efficiency begins to fall considerably, if the nozzle outlet moves away from this optimum position. For example, ejector efficiency decreases by approximately 20 % if the nozzle is moved backward 10 mm or forward 20 mm. Furthermore, for a large expansion angle of say 5°, the outlet position could be moved slightly into the diffuser to maximize the ejector efficiency. Also, the efficiency of the ejector decreases slightly with increasing diffuser expansion angle.

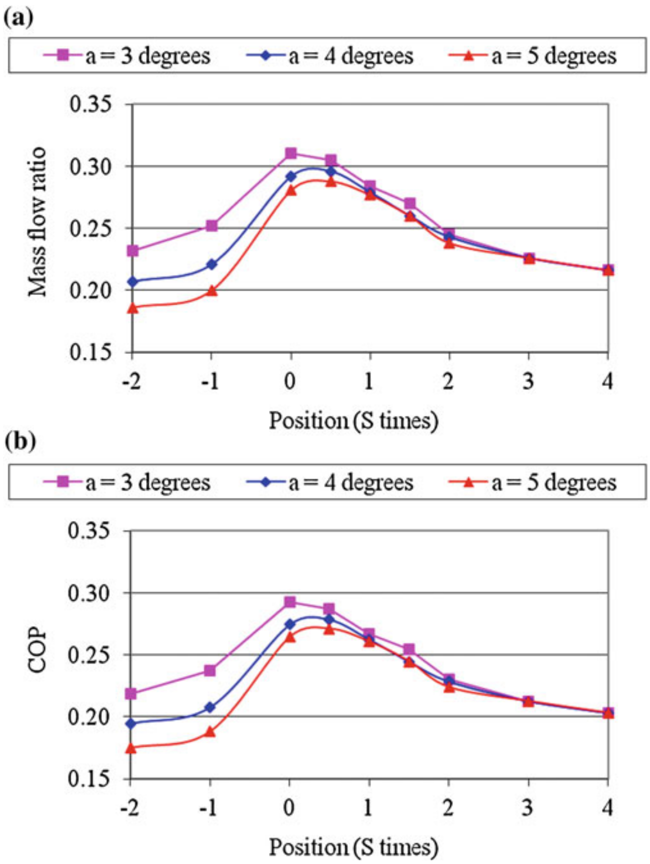


**Fig. 13.10** Variations of entrainment ratio and COP with nozzle position of the ejector for three diffuser expansion angles **a** Mass flow ratio **b** Coefficient of performance

## 13.5 Simulation of Ground-Coupled Heat Exchanger

A heat exchanger is required to transfer heat between the soil and the refrigerant, for a ground-coupled heat pump that uses a horizontal loop system, as shown in Figure 13.11. Heat transfer (transient state) from soil, to a horizontal straight heat exchanger for heating operation, is simulated using an in-house computer program that has been specifically developed to simulate dynamic thermal interactions between the soil, heat exchanger, refrigerant, and ambient conditions.

Specifications and concerns regarding the heat exchanger simulation are as follows:

- The heat exchanger is made of high density polyethylene with an external diameter of 40 mm, thermal conductivity of 0.46 W/m K, and is installed horizontally at 1.2 m below the ground surface;
- The refrigerant (at −1 °C) is a mixture of water and antifreeze and flows in the heat exchanger at a mean velocity of 0.4 m/s;
- Soil density is 1588 kg/m$^3$, has specific heat of 1465 J/kg K, and thermal conductivity of 1.2 W/m K;
- Deep soil temperature is assumed at 10 °C;
- Ambient air is modeled at 5 °C with a wind speed of 2 m/s measured at 2 m above ground height (for rural areas) and approximately 4 m/s (for urban areas).

The initial temperature of soil and heat exchanger is set to be the same as that of deep soil. For simulation of operating a GSHP in a specific site and season, the initial soil temperature can be set to vary with depth according to its annual variations with time and depth (e.g., a sinusoidal relationship). Similarly, the air temperature and wind speed can also vary with time from daily to annual variations.

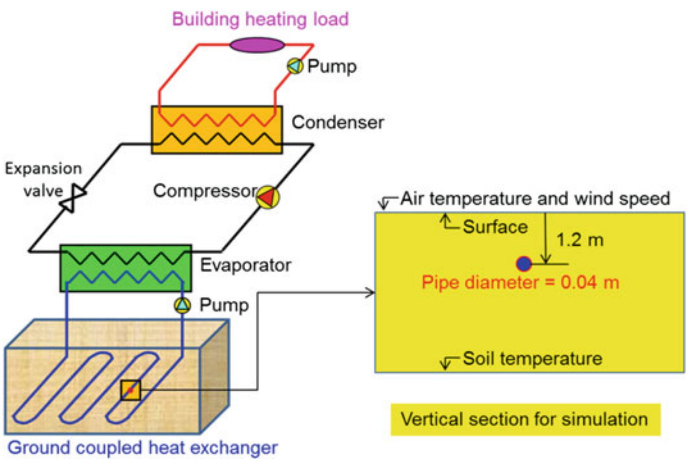


**Fig. 13.11** Schematic diagram of the horizontally coupled ground source heat pump

Figure 13.12 shows predicted soil temperatures and heat transfer rate for the heat exchanger under continuous operation over a period of time. In the vertical direction, the downward heat transfer is taken to be positive and upward heat transfer is negative. Heat transfers from the warm soil to the cold heat exchanger from all directions. Heat from soil above the heat exchanger is also lost to cold air in the early stages of operation when the soil is warmer than air. For example, after 24-hours of operation, heat loss (to air) from the soil reaches about the mid distance of the installation depth for the heat exchanger. For long-term operation, heat will evenly transfer to the heat exchanger, not only from the deep soil but also from air, if the refrigerant is kept much colder than air. This would occur after one month using the simulation conditions. Variations of temperature and heat transfer during the first 24-hours are limited to about 0.9 m from the heat exchanger. After the 10th and 30th (continuous) operating days, temperature variation extends to about 2.8 m and 4.5 m from the heat exchanger, respectively.

The temperature of the heat exchanger (external surface) also varies with time as shown in Fig. 5.3a. When assessing temperature drop and duration, it takes

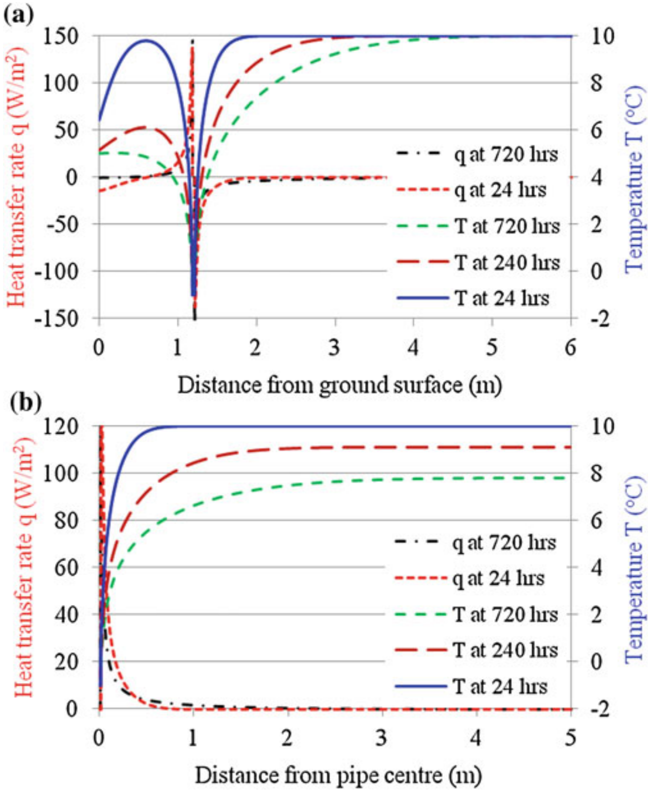


**Fig. 13.12** Predicted variations in soil temperature and heat transfer **a** Vertical direction and **b** Horizontal direction

about 18 min for the heat exchanger to fall from 10 °C to 5 °C and 7 h from 10 °C to 1 °C. Temperature falls to freezing point (with continuous operation) after approximately 18.5 days with refrigerant at −1 °C. For intermittent operation for 12 h a day, the temperature would remain above the freezing point, even after one month. When the system is switched off, heat exchanger and soil temperatures gradually increase as heat is transferred from the surrounding soil, but heat exchanger temperatures do not recover to initial soil temperatures with a 12 h period. Consequently, the heat extraction capacity decreases on a daily basis, as discussed in further detail (Fig. 13.13b).

The *specific heat extraction* (rate) is the metric, generally used to evaluate the capacity of a ground-coupled heat exchanger. It is defined as: 'the heat transfer rate per unit length of the heat exchanger'. At the start of the simulation, the predicted specific heat extraction value (Fig. 13.13b) is very high (over 100 W/m) because of large temperature differences between surrounding soil and the refrigerant. However, for continuous operation, it decreases rapidly to less than 50 W/m within 0.17 h, 23 W/m in 8 h, 20 W/m in 21 h, and drops to less than 20 W/m before the end of the first day. The average specific heat extraction is 28, 26, and 23.3 W/m for the first 8, 12, and 24 h of operation, respectively. For longer periods of operation, the specific heat extraction decreases. For example, the daily average heat extraction is just under 16, 14, 12, and 11 W/m for the 5th, 10th, 20th, and 30th day, respectively. The average value is much lower than those used for borehole design specification which is about 5 W/m per degree temperature difference between the far-field soil and refrigerant (EST 2004), or 55 W/m for simulation conditions. Assuming that the specific heat extraction for a horizontal heat exchanger is half that of a vertical heat exchanger (i.e., 27.5 W/m), then predicted specific heat extraction for the horizontally coupled heat exchanger is much lower for longer operating periods. Hence, the total length of a heat exchanger would be greatly undersized for horizontal-coupled systems, if one adopted (the more commonly used) design principles for borehole heat exchangers (vertically-coupled). If such mistake was to occur, resulting COP values would be lower than expected. Even for intermittent operation, specific heat extraction would be less than expected too, as seen in Fig. 13.13 (12 h daily operation from 8 am to 8 pm). In fact, the specific heat extraction for intermittent operation is between 10 and 27 % higher than for continuous operation. Average specific heat extraction decreases from 26 W/m for the 1st day, to 15 W/m on the 30th day. Unsurprisingly, heat extraction also depends on other factors such as soil property, ambient air and operating conditions. CFD can be used to assess the influence of all these factors on system performance or for system design.

Simulation time steps should be sufficiently small when emulating transient state heat flow through a horizontally coupled earth heat exchanger. In doing so, it captures rapid temperature changes which are present at the beginning of operation near ground surface level, due to coupled convection and conducted heat transfer, as well as potential radiation and evaporation between ambient air and soil. If initial soil temperatures differ significantly from those of the source/sink material, or ambient conditions, a small time step (e.g., one second) will be required to

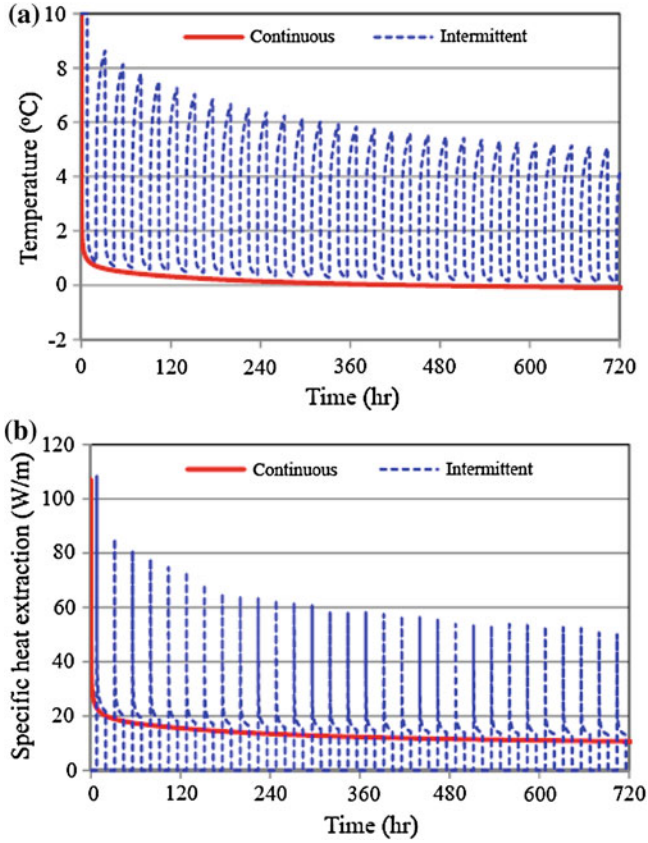


**Fig. 13.13** Predicted variations with time of pipe temperature and specific heat extraction. **a** Pipe surface temperature. **b** Specific heat extraction

facilitate accurate simulation of variations in soil temperature, and heat extraction rate for the first few minutes of operation. As time progresses, time steps can be increased, after continuous operation for one whole day, to say one minute. An excessive time step from simulation start can lead to under prediction of the pipe surface temperature changes, and heat extraction rates for continuous operation. It would fail to capture changes at the early stages for both continuous and intermittent operation, which would result in errors predicting long-term intermittent operation (or continuous operation) with varying ambient and operating conditions. However, it is very time-consuming if small time steps (increasing from 1 s to 30 s) are used for the whole duration, due to sudden temperature changes near times when the system is switched on and off. As an indication, it would take a PC (3 GHz and 3 GB RAM) nearly 12 h to complete a simulation of 2D flow for one day's intermittent operation. Hence, it is sometimes necessary to perform simulations on a high specification PC when simulating, for example, transient 3D heat flow through a ground-coupled heat exchanger over a year's duration.

To reenforce the importance in selecting appropriate time steps, additional simulations (time step of 10 min) using the same conditions were conducted for continuous and intermittent operation. Figure 13.14 shows the relative difference in pipe surface temperature, (defined as the ratio of temperature difference between: a simulation with a constant time step of 10 min, and a more accurate simulation starting with a time step of one second, to the temperature from the more accurate simulation) for continuous operation is 0.3 at the 10th minute of operation.

The relative difference decreases to about 21 % at the end of the first day. It reaches a minimum of 17 % after 3 days and then increases with decreasing pipe temperature. The relative difference becomes very large (well over 100 %), when the pipe temperature from the more accurate simulation approaches 0 °C when it turns negative at pipe temperatures below 0 °C which is also predicted using the

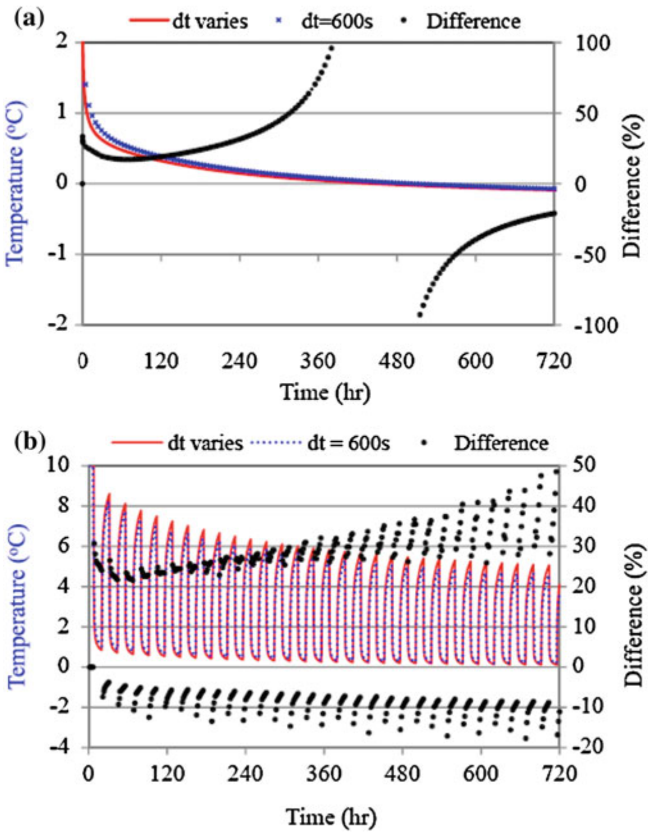


**Fig. 13.14** Effect of time step (dt) on the predicted pipe temperature. **a** Continuous operation. **b** Intermittent operation

constant time step 60 h later. The relative difference decreases once more, to less than 21 and 10 % after continuous operation for 30 and 40 days, respectively. For intermittent operation, however, the relative difference would generally increase with time for both the on and off periods, and the difference is larger for the on period than the off period. When continually using a large time step, changes in pipe temperature are also under-predicted, such that predictions are higher when the system is switched on, but lower when the system is off.

## 13.6 Conclusion

CFD is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the necessary calculations to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. Ongoing research yields software that improves the accuracy and speed of complex simulation such as transonic or turbulent flows. Initial validation of such software is performed using a wind tunnel for instance, with final validation being full-scale testing (i.e., the final product under evaluation). CFD involves numerical methods and algorithms which deal with mass continuity, momentum, turbulence, and enthalpy to derive solutions to engineering problems and the like. Three case studies demonstrate that CFD is an extremely powerful tool that can be applied to many situations in the field of sustainability in order to analyze fluid (air) and heat flows, including those concerned building design.

The first simulation shows that a naturally ventilated office building with a solar-heated double skin facade can generate sufficient buoyancy-driven ventilation, and wind impact becomes dominant when wind reaches certain speed. Also, wind can adversely affect buoyancy-driven ventilation. The second simulation looks at the performance of a solar-powered ejector; in particular, the position of the primary nozzle and its outlet near the diffuser entrance. The third simulation analyzes a heat exchanger, showing that the heat extraction/injection capacity of a horizontally coupled earth heat exchanger is found to decrease with increasing operating time; hence, consideration should be given to the design of the ground-coupled earth heat exchanger for heat pumps. A larger/longer heat exchanger is required for longer term and more frequent operation.

CFD can be used for optimization and/or assessing performance of not only situations featured here, but also other sustainable technologies and solutions. Types of other CFD applications which are concerned with the flow mechanisms presented above include: (1) building-integrated photovoltaics and wind turbines for electricity generation or ventilation enhancement; (2) heat pipes for ventilation heat recovery and for application in a thermal diode wall; (3) earth-to-air heat exchangers for preheating/cooling of supply air to buildings; (4) phase change materials for energy storage; (5) sustainable building structures such as green roofs/walls; (6) energy-pile foundation; (7) multifunctional facades; and (8) thermal mass for energy storage and temperature tempering; or various combinations of the aforementioned. The use of CFD techniques will become increasingly relied upon as our built environment emerges with passive design solutions and low energy building systems. As computing technology develops and dazzling processing speeds become the norm, CFD will become more widely used and accessible through smarter and more interactive user interfaces.

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# Chapter 14
# Occupant Behavior and Building Performance

**Baizhan Li and David Lim**

**Abstract** People and building performance are intimately linked. This chapter focuses on the issue of occupant behavior; principally, its impact, and the influence of building performance on occupants. The early sections looked at how energy is consumed in buildings and identifies the range of occupant-interactive opportunity. The issue of post occupancy evaluation (POE) is covered, exposing the concept of the energy performance gap and why discrepancies occur. The emphasis then shifts toward building performance, particularly indoor environment, how it impinges on work productivity, and how it is measured. Later sections discuss occupant adaptation in achieving thermal comfort, in addition to, the role of energy management systems, smart-sensor networks, and data mining with occupant behavior as the backdrop. Finally, the chapter closes by looking at how occupants fit within the framework of building performance assessment. *Learning outcomes*: on successful completion of this chapter, readers will: (1) Appreciate the need to better understand how occupants behave in buildings due to their magnitude of impact on energy use; (2) Understand the range of occupant behavior including: interactive opportunity; (3) Understand adaptation in achieving indoor comfort and response to indoor environment and work productivity; (4) Gain insight into the role of POE and its importance in developing improvement cycles; (5) Grasp how technology and occupant behavior can be integrated to realize energy savings and increase the quality of indoor environments; and (6) Know about building performance assessment.

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**Keywords** Building energy performance · Energy management systems · Occupant behavior · Post occupancy evaluation

## 14.1 Introduction

People and buildings are inextricably linked. And, buildings largely consume energy as a direct response to its occupant's needs. It is reported that buildings are responsible for approximately 40 % of energy use in many countries (BRE 2011). Undoubtedly, this energy mostly derives from fossil fuels which contribute to climate change. Worldwide building energy consumption is expected to grow in the region of 45 % over the next 20 years (World Business Council for Sustainable Development 2008), driven by nations such as China, India, and Brazil. The climate change and sustainability agenda has ushered in a new phase of policy mechanisms that are bringing about a wave of innovative construction systems and methods to conserve energy use. Through tightening building regulations and planning policy, governments worldwide have realized that our built environment plays a key role in mitigating the devastating effects of climate change and global warming. Frustratingly, although building design can be regulated to some degree, the same cannot be said for its occupants.

Ideally, buildings should be designed to provide a suite of amenities whereby their indoor environments ensure occupant satisfaction and bolster productivity in the workplace. Therefore, the quality of a building's physical environment, its air quality, thermal comfort level, luminance, and acoustic characteristic, has a direct impact on its occupants. Buildings become more than just a shell in which we go about our daily lives. They shape our psychological and physiological reactions; their design can add value to our personal relationships and conversely, diminish our wellbeing and happiness (Farshchi and Fischer 2000).

Across the wide range of building types, including domestic, industrial, commercial, public sector, and other classes, buildings consume energy in a multitude of ways. A simple review of a building's energy end-uses identifies the demands. Buildings ought to be designed and serviced to provide its occupants with a healthy, functional and supportive environment which fosters social, physiological, and psychological wellbeing. In addition, the service technology and elements within a building (e.g., controls, windows, vents etc.,) are designed and installed to function in a given manner, usually in response to internal and external stimuli; weather for instance. In the majority of cases, occupants are required to facilitate its correct operation. This does not always materialize: energy is wasted, indoor environments become uncomfortable, utility bills soar, building system components require undue maintenance, and in general, the relationship between building and user deteriorates. In summary, occupant behavior is vital for the successful operation and energy efficiency of sustainable built environments.

This chapter explores the complex relationship between occupant and building, unearthing the socio-technical challenges involved in delivering sustainable environments that work in concert with modern day life and human needs. In order to discuss such issues, holistically involves unearthing answers to questions such as: how do occupants achieve thermal comfort; how do they interact with control mechanisms; how do social dynamics impact on individual and collective behavior; and what psychological and physiological processes underpin energy related behaviors? Throughout the chapter, occupants are largely referred to nondomestic contexts, office environments mainly; however domestic situations also furnish discussions.

## 14.2 Energy in Buildings

Energy end-use across different building types is very similar, although proportional use and energy use patterns can differ greatly. Regarding general usage, building energy consumption can be classified into two areas: *non-domestic* and *domestic*. Typically, energy end-uses for nondomestic buildings include heating, ventilation, air conditioning, and cooling; office appliances (copier, fax, computers, etc.), kitchens (catering or small), other building service systems (security, control mechanisms), and lighting. This is similar for domestic buildings but naturally there are fewer office appliances and building service systems are smaller in scale. The other noticeable difference between the two sectors is the level of available control. Unsurprisingly, occupants in nondomestic buildings commonly experience a reduced level of control and engagement with indoor environments, whereas domestic occupants are more 'hands-on'.

Energy demand can be categorized into two types of determinants: *behavioral* and *physical* (Yao and Steemers 2005). Behavioral determinants are little related to climate, but strongly related to a household's human dimension. These include factors such as: occupant density, occupancy patterns, attitudes, beliefs, and occupant interaction with building services and technology. These all tend to be highly correlated with people's habits and seasonality (e.g., heating). Mansouri et al. (1996) discuss the relationship between household electricity end-use and behavior. They comment that, behavioral determinants such as appliance use, involve relatively 'flexible' decisions, which are made on an hourly, daily, weekly timescale. Physical determinants however are related to climate and building design, and have a low correlation with people's habits. The physical determinants of energy use, such as dwelling size, building design, and the space-heating system for instance, are the results of relatively fixed decisions. The use of heating and cooling energy for thermal comfort is also related to occupancy pattern and household income. For example, many households turn down the heating temperature when the house is unoccupied or during the night. Most energy end uses relate to both behavioral and physical determinants, and are largely influenced by occupancy patterns.

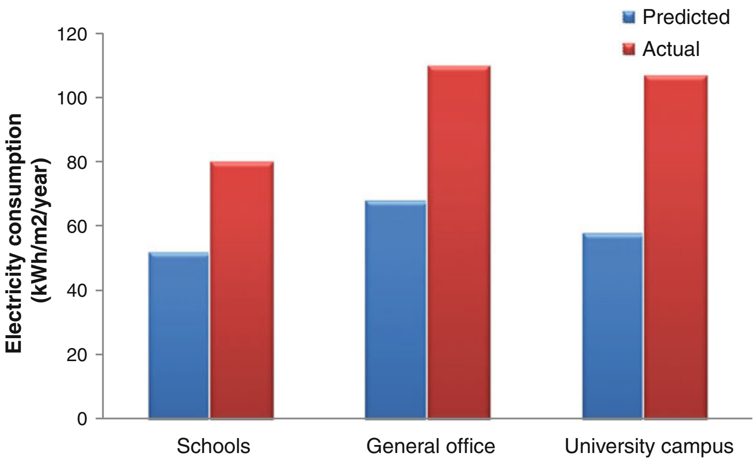


**Fig. 14.1** CarbonBuzz median electricity consumption by sector: predicted versus actual (Adapted from Menezes et al. 2011)

## 14.3 Post Occupancy Evaluation and Energy Performance

In recent years, the construction industry has come under increasing pressure to deliver high performance low energy buildings. International, national, and local policy has provided a key transport mechanism to facilitate this. In addition, the planning system, building regulations, and green assessment methods have played a vital role. When new buildings projects aim for a certain assessment certification level (e.g., the Standard Assessment Procedure-SAP, in the UK), its design is based on *predicted* energy use, calculated from building energy simulation tools. In many instances an *'energy performance gap'* occurs. This is the difference between *estimated* energy use and *actual* energy use, measured post construction. The two are often not the same. Actual energy use is invariably greater (Bordass et al. 2001, 2004; Demanuele et al. 2010). An online project aimed at understanding the energy performance gap through case studies, found that across three different building sectors, average *actual* energy use was greater in all instances (Fig. 14.1) (Menezes et al. 2011).

The energy performance gap is primarily caused by occupants. For example, it can stem from people's preference for unnecessarily high internal temperatures during heating seasons, or the inability to control systems effectively. Wood and Newborough (2003) cite studies which found that occupant behavior alone was responsible for between 26 and 36 % in the variance of total domestic energy use in three different cases. Other studies report that occupancy issues can vary the energy consumption of identically built houses by a factor of two (Seligman et al. 1978; Baker and Steemers 2000) or even three. A study by Bahaj and James (2007) which looks at the value of photovoltaics, found that the impact of occupant behavior in nine identical social houses could vary electricity demand by 600 % at different times of the year. This mirrors the finding from a report published by the Carbon Trust (2011) who used data from two programs (the Low Carbon Buildings Accelerator and the Low Carbon Buildings Programme) to show that actual building consumption can be up to five times higher than estimated use. Research like this demonstrates how occupant behavior can render predicted energy consumption wildly inaccurate on occasions.

The area of research dedicated to unraveling the mysteries of occupant-related energy use is post occupancy evaluation (POE). One particular focus of POE is concerned with analyzing a building's energy use in the real world, i.e., not on a computer screen during simulations, but as-built, with occupants operating within it. POE is thought as the weakest link in the construction cycle, but ironically, it exists as the most important link if we are to implement continuous improvement cycles. Architects' and engineers' improvement capabilities frequently plateau due to the absence of design feedback. This situation elevates the importance of POE because it acts as crucial feedback and feedforward mechanisms, and aids benchmarking processes to help formulate industry standards (Choi et al. 2012).

The PROBE studies (2002) ran for 7 years; they reviewed the performance of 23 buildings featured in the Building Services Journal (Bordass et al. 2004). PROBE (2011) concluded that predicted energy consumption was typically *half* that of actual energy use. A case study that looked at the energy performance gap in an office building (Menezes et al. 2011) found that integrating monitored energy data into building simulation, could improve its accuracy to within 3 % of actual use. The authors go on to suggest some causal factors of energy performance gaps, stating that factors related to energy *prediction* include: (1) design assumptions (i.e., building simulation input data is inaccurate); and (2) modeling tools (i.e., the capability and underlying equations embedded in the algorithms are questionable). Whereas actual energy use is caused by: (1) management and controls (i.e., occupants are constrained by the quantity and functionality of the control mechanisms); (2) build quality (i.e., air leakage, thermal insulation, building service installations and other construction or material-related deficiencies, negatively impact on performance); and (3) occupant behavior (i.e., people fail to interact with the building as intended). At present, much work is devoted to better understanding of exactly how occupants impact on energy use across all building types and sectors. The next section expands on these issues.

## 14.4 Occupants and Buildings

People spend up to 90 % of their time in buildings; they work, relax, eat, and sleep in buildings; and in countries with extreme climates, this sentiment is of greater relevance. To achieve energy efficiency in a building, energy system operation and management is vital. However, poor operation, poor management and a lack of the knowledge of occupants' behavior and expectation results in significant energy waste. Therefore, understanding occupants' response and interaction with the environment they are exposed to is very important. This section looks at the challenges and opportunities of occupant engagement with buildings.

### *14.4.1 Energy End-Use*

How exactly do occupants impact upon building energy use? In answering this question, a review of a building's energy end-uses provides valuable insight. This includes: heating, ventilating, and air-conditioning systems (HVAC), space heating, space cooling, domestic hot water (DHW), appliances, lighting, and other miscellaneous uses (e.g., security systems, control mechanisms). The scope for occupants to interact with systems associated with these end-uses can widely vary.

Policy mechanisms have increased building standards and energy efficiency. Evidently, engineering solutions facilitate much improved building envelopes and building service systems. What is not always apparent, and fundamental in achieving policy aims, is ease of control. That is, occupant's control over their indoor environment. After all, there is little use of high performance buildings that are difficult to manage. Conversely, energy conscious occupants can become impotent in an uncontrollable building.

### *14.4.2 Occupant Interaction*

The stimuli behind occupant interaction with buildings can be wide ranging. Van Raaij and Verhallen (1982) present an early behavioral model of residential energy use (Fig. 14.2). Some of the most influential factors have been identified. From their model, it can be seen that physiological, psychological, economic, climatic, technological, and physical factors all have a degree of influence. This section highlights the extent to which occupants interact with buildings and the typical barriers to behavioral change.

A similar theoretical model by Yao et al. (2009) looks at adaptive thermal comfort (Fig. 14.3). Their model is based on the 'Black Box' theory, taking into account factors such as culture, climate, social, psychological, and behavioral adaptations, which have an impact on the senses used to detect thermal comfort. The model is called the adaptive predicted mean vote (aPMV) model.

### *14.4.3 Design Related Barriers*

If buildings are to work in concert with occupant behavior, the use of devices and building elements such as: control panels, setting dials/knobs, timing switches,

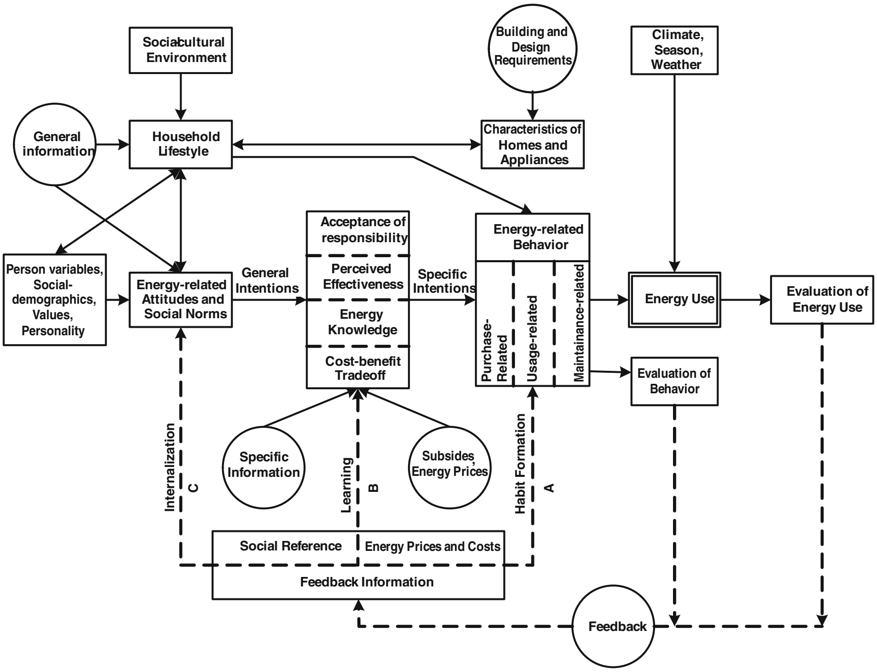


**Fig. 14.2** A behavioral model of residential energy use (Van Raaij 1983)

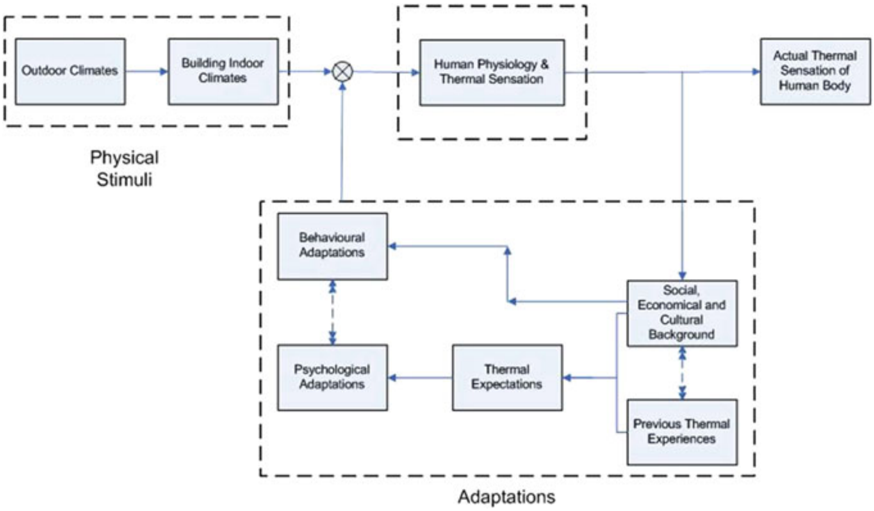


**Fig. 14.3** Mechanism of adaptive thermal comfort (Yao et al. 2009)

**Table 14.1** Barriers to behavioral change

| Cause | Effect | Consequence |
|---|---|---|
| Inaccessible plug sockets | Equipment and appliances are often left on | Increase in stand-by power consumption |
| Inoperable windows | Prohibits natural ventilation for cooling. Reduction in air quality | Excess cooling demand<br>Health-related problems (e.g., headaches) |
| Window access is limited | Occupants do not open/close windows appropriately<br>Occupant discomfort | Excess cooling or heating demand<br>Health- related problems (e.g., headaches) |
| Building service controls (e.g., digital panels, physical controls) are complicated to operate | Incorrectly set, adjusted too infrequently, not used at all | Excess cooling, heating, air conditioning and lighting demand.<br>Occupant discomfort |
| Broken or limited access to controls (e.g., handles, knobs, switches, levers, etc.) | Inability to effectively control building services | Excess cooling, heating, air conditioning, appliance, and lighting demand.<br>Occupant discomfort |
| Poorly designed building service zones | Nonuniform internal environmental conditions | Partial occupancy discomfort |
| Insufficient daylighting | Excess use of artificial lighting | Excess lighting demand<br>Health- related problems |
| Poorly located air vents/ ducts | Non-uniform internal environmental conditions | Partial occupancy discomfort |

push buttons, latches, windows, blinds, vents, fans, light switches, appliances, and the like, should all be accessible and simple to use. If not, energy is likely to be wasted. Table 14.1 shows a selection of common building-related barriers to behavioral change and indoor environmental management.

If we are to successfully manage our building stock (new and old properties) in an efficient manner, occupants, operators, and facilities managers must be able to easily control building service systems and use them to their full capability. A fundamental goal of high performance buildings is to avoid the types of problems described above; and instead, create intelligent systems (manual and automated) to best control building services. This is often a complex task.

Occupants' needs frequently override the stays of technology and what it is intended for. In search of comfort, 'work-around' solutions are often devised to overcome technological constraints. This is a 'user problem' embedded in socio-technical design which leads to crude solutions involving sticky tapes, tacks, props, and other makeshift contraptions to hold switches down, vents open, windows ajar, and openings covered etc. Figure 14.4 shows a taped office window to reduce air infiltration; however, on warmer days, the window's inoperability may increase cooling demand by prohibiting natural ventilation opportunities.

**Fig. 14.4** A taped window to reduce air infiltration

### *14.4.4 Management Related Barriers*

Establishing an energy policy for nondomestic properties is essential for coordinating energy conservation behavior. For example, occupants must be aware of opening windows, while air-conditioning systems are in operation. Similarly, awareness of heating system schedules allows occupants to dress accordingly to achieve thermal comfort.

Another typical management-related issue which stifles energy conservation is the poor commissioning of buildings, or bad 'hand-over' practices. This is characterized by situations where engineers meticulously design successful systems, but clients (occupants) fail to use them correctly. For example, control panels are regularly underused or remain in programs set by the installation company. To compound this, operating procedures are commonly unexplained and manuals are difficult to understand or not supplied, when new occupants move into a building.

### *14.4.5 Sociological Related Barriers*

Humans are social beings. We live together in groups and work together, in some instances, on office floors sprawled with many workstations. The relationships occupants develop with one another, fused with the hierarchy of organizational structures, can shape our behavior and how we interact with buildings to some degree.

Multi-occupied spaces can be challenging to manage. A commonly reported issue, and an area of contention, is that of comfort in open plan office spaces. People have a wide ranging perception of what is comfortable. This can be variation in temperature, ventilation rate (air quality), humidity, luminance, or noise level. Disputes frequently arise from occupants who are too cold (sitting next to windows), while their colleagues, sitting near the center zones of a room, are too hot. Similarly, occupants sitting directly under air-conditioning vents complain of being too cold when external temperatures are high, e.g., in excess of 30 °C. If temperature settings in an air-conditioned room are set to satisfy the one occupant who ‘prefers cooler’, then others will have to adapt, using more clothing layers for example, resulting in wasted cooling energy. Office politics, social dynamics, and genuine differences in comfort expectation and experience, are complex issues to solve when aggregated given crude building service controls.

### *14.4.6 Challenges and Opportunities*

Influencing change in occupant behavior is extremely challenging. A behavioral duality often emerges whereby people exhibit energy conscious behavior at home, but not at work. Hence, solely relying on the occupant’s good nature and sense of responsibility to behavior accordingly, rarely produces the desired outcome.

People’s routines, ingrained behavior and habits are exceptionally difficult to break. Historically, legislation has had a huge influence on behavioral change, but for instance, policies prohibiting occupants from leaving their computers on overnight, have not yet emerged. In any case, is it morally correct to implement such an approach?

Indeed, technology and design have a key role to play. The inclusion and use of well-managed on-site control systems, feedback displays (Darby 2006), centralized or remote energy management software, passive infrared (PIR), radio frequency (RF), and other wireless sensors, appliances with dynamic demand management capability and SMS devices, all have a promising future in building energy conservation. Designing ‘out’ or excluding certain building features can be a direct and effective approach to incite behavioral change (e.g., replacing baths with shower cubicles). Education in the form of awareness campaigns, signage, verbal, and written communication and energy programs in schools have a potential to impact on behavior too. A study investigating the energy-saving potential of Chinese residents through energy-saving education (Ouyang and Hokao 2009), found that ‘improved’ behavior can save more than 10 % of household electricity use. Whatever means are implemented, there are opportunities to be explored, but the challenges associated with changing behavior on mass are considerable.

## 14.5 Building Performance and Productivity

Intertwined with the relationship between occupant and building, is the issue of *productivity*. Defined as: ‘the rate of output per unit of input’, productivity in buildings is influenced by four cardinal factors: personal, social, organizational, and environmental (Clements-Croome 2004). Building design and indoor environment can impact on all of these. Office workers and other types of employees can spend anything from 20 to 60 hours a week at their desk, on factory floors, or in other indoor environments; and in some cases even longer. It is generally accepted that a poor working environments hinders work output. This section delves into this issue in greater detail.

### 14.5.1 Measurement of Productivity

Measuring productivity, as one might expect, is a challenging task encompassing many variables. It involves investigating a range of metrics such as: concentration level, technical competence, organization and management effectiveness, environment, and wellbeing. Up until the late 1990s, there was an absence of robust methods in which to conduct such an exercise; however, nowadays there are rigorous ways to gage productivity.

Ilgen and Schneider (1991) proposed three approaches to measure productivity: physiological, objective, and subjective. Although physiological methods in measuring work stress exhibited through the nervous system appeared logical, it was intrusive. Obtaining reliable results requires unobtrusive methods. The study of alpha and beta brain waves, speech pattern (Shiomi and Hirose 2000), and cerebral blood oxygen (Nishiara et al. 2002) can be conducted to identify emotional states as a less obtrusive means. Work by Wyon (1996) describes six productivity metrics including: (1) *simulated work* (people perform routine tasks in lab conditions); (2) *diagnostic test* (people conduct unrealistic test tasks); (3) *embedded tasks* (metric is calculated from existing tasks); (4) *existing measures* (metrics are made available); (5) *absenteeism* (days off work); and (6) *self-estimates* (people report perceived levels of efficiency and effectiveness). Wyon suggests testing these metrics individually with a linked hypothesis.

### 14.5.2 Subjective Measures

Subjective ways of measuring productivity focus on the individual's moods, attitudes, and opinions. Using survey methods shows that productivity is strongly correlated with the working environment, job satisfaction, and crowded workspaces (Clements-Croome 2000). Interestingly, closely related work shows that productivity could be improved by approximately 10 % through improvements in office environmental conditions alone (Li 1998). With various assumptions, productivity in other buildings types could show either higher or lower levels of improvement. Nevertheless, Li's work demonstrated that his method is robust and highly effective in assessing productivity. Further work by Clements-Croome and Li (1995) realize the potential of the occupational stress indicator (OSI) whereby introducing an environmental component within it. Parameters such as internal temperature, ventilation, humidity, air quality, lighting, noise, and work space distribution have subsequently been integrated (Clements-Croome and Li 1995).

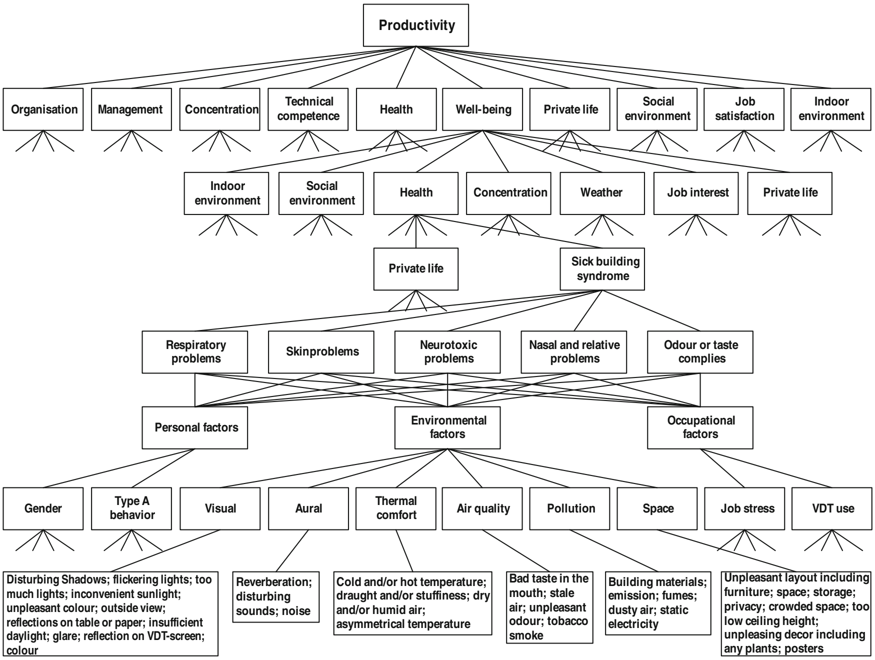


**Fig. 14.5** Priority factors influencing productivity and wellbeing of occupants for use in AHP model

There is no simple relationship between single environmental factors and human behavior (Li 1998). In his work, questionnaires were analyzed using the analytic hierarchy process (AHP) method (Saaty 1972) with multiregression and correlation analysis to establish an empirical model of ‘multisensory’ occupant wellbeing. These factors are then arranged in successive layers or hierarchies through which the analytic hierarchical model has been developed. The importance of the factors in the lowest hierarchy can be related to those in the highest hierarchy on the basis of the results from the questionnaires and semistructured interviews (Li 1998). Figure 14.5 shows the approach.

The *Spearman rank-correlation coefficient* was then used to assess measures of association between any two variables. It was shown that a significant rank correlation exists between self-assessed productivity and environment and job dissatisfaction and job stress, as shown in Table 14.2.

Dissatisfaction with the environment arose from a number of issues: personal health ($r = 0.34$), sick building syndrome symptoms ($r = 0.35$), visual and aural problems ($r = 0.36$), thermal problems ($r = 0.49$), and crowded workspace ($r = 0.50$). The correlation coefficients ($r$) were statistically significant for $p < 0.01$. Other issues include social ambience, layout, sense of space, and color.

Regression analysis gave significant positive correlations between a poor working environment and job dissatisfaction, job stress, crowding, and thermal

**Table 14.2** Association between self-assessed productivity, environment and job factors (Li 1998)

| Factor | Associated factor | Spearman rank-correlation coefficient |
|---|---|---|
| Self-assessed productivity | Unsatisfactory indoor environment | −0.49 |
| | Job dissatisfaction | −0.36 |
| | Job stress | −0.21 |
| Unsatisfactory indoor environment | Job stress | +0.31 |
| | Job dissatisfaction | +0.43 |
| Job stress | Job dissatisfaction | +0.36 |

problems; and job dissatisfaction and job stress. Likewise, analysis also showed that self-assessed productivity decreased with poor environments; job dissatisfaction; crowded workspaces; and the number of people in the room.

The regression Eqation (14.1) for an overall satisfactory indoor environment was shown to be:

$$\begin{aligned} \mathrm{En} = -0.7211 + 0.5997 * \ \mathrm{Th} + 0.4082 * \ \mathrm{SBS} + 0.3222 * \ \mathrm{CS} \\ (r = 0.6546, F = 36.99 > F = 0.01[3, 152] = 3.92) \end{aligned} \tag{14.1}$$

where En is ‘poor indoor environment’; SBS is ‘suffer from Sick Building Syndrome symptoms’; Th is ‘suffer from thermal conditions’; and CS is ‘crowded working spaces’; $r$ is the correlation coefficient; and $F$ is Statistical $F$–test.

This implies that subjects who suffer from physical environmental factors will increasingly suffer from thermal-related problems, crowded workspaces, and sick building syndrome symptoms.

The multiple regression Equation (14.2) for job dissatisfaction was found to be:

$$\begin{aligned} \mathrm{JD} = 1.2055 + 0.3157 * \mathrm{JS} + 0.2572 * \ \mathrm{En} + 0.1023 * \ \mathrm{CS} \\ (r = 0.5367, F = 19.56 > F = 0.01[3, 149] = 3.92) \end{aligned} \tag{14.2}$$

where JD is ‘job dissatisfaction’; JS is ‘job stress’; En is ‘poor indoor environment’; and CS is ‘crowded working spaces’.

This shows that high job dissatisfaction results from job stress, crowded workspace and an overall unsatisfactory environment. For self-assessed productivity, the regression Equation (14.3) was developed using a stepwise regression procedure:

$$\begin{aligned} \mathrm{SAP} = 6.8510 - 0.3625 * \ \mathrm{En} - 0.1542 * \ \mathrm{JD} - 0.1329 * \ \mathrm{CS} \\ (r = 0.5083, F = 14.86 > F = 0.01[3, 132] = 3.94) \end{aligned} \tag{14.3}$$

where SAP is ‘self-assessed productivity’; En is ‘poor indoor environment’; JD is ‘job dissatisfaction’; and CS is ‘crowded working spaces’.

A distinction was made between *direct* effects, which do not result from any other variable in the model, and *indirect* effects, which arise from interaction between variables (Cohen and Cohen 1983). For example, a poor environment has a direct effect on self-assessed productivity, but there is also an indirect effect, because poor environments affect job satisfaction, which in turn affect self-assessed productivity. The total indirect effect is estimated by the product of the effects of an overall unsatisfactory environment on job satisfaction, and job satisfaction on self-assessed productivity. The total effect of environment on self-assessed productivity is the result of combining direct and indirect effects (Li 1998). Further analysis showed that the most common complaints about unsatisfactory environments were those connected with high or low temperature variations; stale and stuffy air; and dry or humid air. Li principally concluded that the majority of respondents believe that their office environment has a direct influence on their wellbeing and self-assessed productivity. Unsurprisingly, this echoes Heerwagen's (1998) research which also concluded that: '*building design can contribute positively to human well-being and performance*'.

## 14.6 Thermal Comfort

Thermal comfort is arguably one of the most noticeable factors occupants become aware of when entering a building. If the environment is too hot or cold, we can adapt. People 'adjust' to improve their wellbeing through physiological, psychological, and behavioral reactions to environmental stimuli—temperature being one. We define these actions as 'occupant behavior'.

Physiological balance of human body can be achieved as a result of the gradual diminution in the strain induced by these stimuli. Perspiration, vasoconstriction, and vasodilatation are common forms of physiological adaptation which play a key role in maintaining human thermal equilibrium. Psychological reactions to thermal and other environmental stimuli are also important and commonly lead to various actions (e.g., switching heating and lighting on/off, opening/closing windows, putting clothes on/off, etc.). People's expectations about how their actions will affect their environment also influence behavior, which in turn, affects building performance and energy consumption.

Two kinds of approaches exist in contemporary thermal comfort research: they are heat balance models based on laboratory studies and adaptive models based on field studies (Yao et al. 2009). The classic work of Fanger related thermal sensation to the existence of heat balance by observing a large number of people in laboratory experiments (Fanger 1970). Fanger has established a lab-based PMV–PPD method (Predicted Mean Vote-Predicted Percentage Dissatisfied). The work of Humphreys, based on his survey of field studies (Humphreys 1978), has concluded that preferred temperatures are variable, responding to the monthly mean ambient temperature. Both methods have been supported by a large number of laboratory and field studies.

There are three categories of self-regulation: physiological, psychological, and behavioral adaptations (de Dear and Brager 1998, Brager and de Dear 1998).

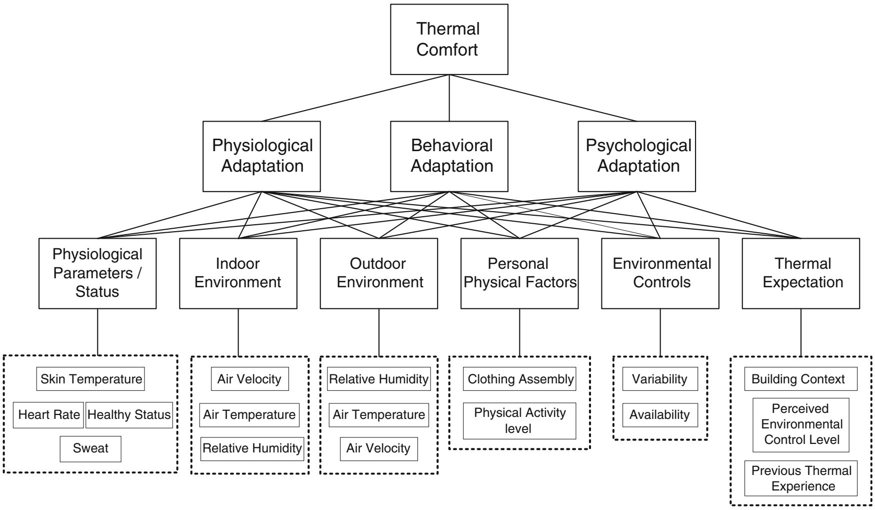


**Fig. 14.6** Analytic hierarchy process method for thermal comfort

However, little is known about the weight of individual contributions of these three categories. Liu et al. (2012a) use the analytic hierarchy process (AHP) (Fig. 14.6) to quantify proportionate contribution of physiological, behavioral, and psychological adaptation and also consider six possible adaptation alternatives (physiological indices/health status, indoor environment, outdoor environment, personal physical factors, environmental control, and thermal expectation).

The study of adaptive thermal comfort is essential for developing suitable thermal environment standards that help shape building legislation, technical requirements, and policies worldwide. This section looks at the issues that determine how occupants adapt to achieve thermal comfort, adaptation types and how to quantify the contributing factors.

### *14.6.1 Determinants of Adaptive Thermal Comfort*

By asking the question of what determines occupant behavior when attempting to achieve thermal comfort, we can begin to understand the underlying motivations that lead to different behaviors. Generally, determinants can be classified into five groups: physical, climatic, environmental, economic, and cultural. Table 14.3 shows some typical behavioral cause and effect patterns within each determinant class.

It can be seen that thermal comfort behavior is motivated by many factors, leading to actions involving personal heating and cooling devices, clothing level, consumption of drinks, etc. The ‘effects’ listed in Table 14.3 feature some typical adaptive behaviors; the following sections explore this in greater detail.

**Table 14.3** Behavioral determinants and examples of cause and effects

| Determinant class | Factor | Cause | Effect |
|---|---|---|---|
| Physical | Large spaces | Variations of indoor environmental quality | Partial discomfort, use of personal heaters etc. |
| | Small spaces | Overcrowding | Noise level, excess heat, use of personal cooling devices |
| | Old buildings | Difficult to service | Discomfort and use of personal equipment to compensate |
| | Building orientation | Located on cooler north side (not south elevation) | Increased clothing level and use of personal heating devices |
| Climatic | Extreme hot days | Overheating | Use of personal cooling, reduced clothing and drinks |
| | Extreme cold days | Underheating | Use of personal heaters, increased clothing and hot drinks |
| Environmental | HVAC system | Lack of zoning controls Too hot/cold/stuffy etc. | Adaptation on all levels |
| Economic | High fuel bills | High heat demand | Increased clothing level, underheated rooms |
| | Not responsible for fuel bill payment | Nondomestic workplaces | Overheated spaces, reduced clothing level, and cooling demand |
| Cultural | Climate | Typical hot weather | Thermal discomfort if new to country. Cold drinks and use of personal cooling devices |
| | Religion | Custom dress | Thermal discomfort: cooling demand and cold drinks |

### *14.6.2 Physiological Adaptation*

The category of physiological adaptation is akin to human thermal regulation. It comprises two further subcategories: *genetic adaptation* (generational) and *acclimatization* (within one generation). The average skin temperature of sedentary occupants changes in response to variations in ambient air temperature (Gagge et al. 1967); however, changes of skin temperature become less apparent when ambient air is over 28 °C. The principle means of physiological adaptation is *vasoconstriction* and *vasodilation.* These terms describe the body's way of regulating internal temperature by controlling blood flow near the skin's surface. *Sweating* and *shivering* are two other common forms of physiological adaptation in response to extreme ambient temperatures. Through a combination of these involuntary responses, occupants can adapt physiologically to their thermal environment when attempting to achieve thermal comfort.

### 14.6.3 Psychological Adaptation

Psychological adaptation is concerned with altering the perception of one's thermal experience (e.g., fire walking). While physical variables remain unchanged, psychological events can alter thermal perception so that a temperature 'feels' more acceptable. For example, occupants' previous experiences of thermal comfort may shape how they perceive the immediate temperature (Liu et al. 2012a); or, repeated exposure to a given climate, say in the dessert, can reduce psychological sensitivity to hot environments. This results in a relaxation of expectations induced by the magnitude of the sensitivity (Auliciems 1981). Habituation is the term that describes the tolerance of repeated exposure, to a climatic and socioeconomic environment in this case.

Interestingly, psychologists discovered that the level of control an occupant exerts over their indoor environment, can influence their perception and irritation level (de Dear and Brager 1998). Liu et al. state: '*People's control over creating a comfortable thermal environment not only enhances the thermal acceptability and percentage satisfaction with the outcome but also affect the building energy consumption and greenhouse gas emissions*' (Liu et al. 2012b). This notion is symptomatic of many unsuccessful modern day buildings. User-centered architecture must be at the core of design when striving for energy efficiency.

### 14.6.4 Behavioral Adaptation

Observing and measuring *behavioral* adaptation is more straightforward compared with studying psychological and physiological modifications. It simply involves noting actions. Behavioral adaptation is divided into three further subcategories: (1) personal (e.g., clothing), technological, (e.g., switching on a fan) and cultural responses (e.g., religious practices). Typical behavioral adaptations are in response to regaining the body's heat balance; this can involve using clothing, drinks, or appliances for instance. Physical factors, e.g., building orientation, or climatic factors such as intense sun, are both catalysts of behavioral adaptation. In their study, Liu et al. (2012b) found that during spring and autumn, occupants tended not to use technological adaptation, but instead used clothing level and beverages to attain comfort in China.

The scope for occupants to change their thermal experience, are termed: *adaptive opportunity* (Haldi and Robinson 2009) and *adaptive constraint* (Baker and Standeven 1994). Within this range, occupants are influenced by multiple factors such as: climate, culture, and economics, level of availability/accessibility of control and regulatory actions, individual characteristics, and the occupants' previous thermal experience.

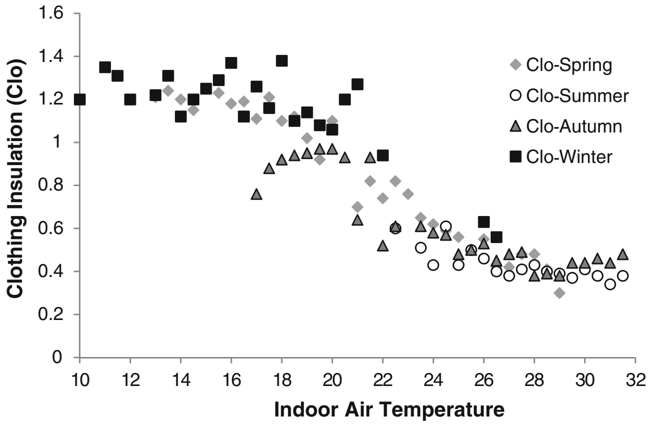


**Fig. 14.7** Variation of clothing insulation with indoor air temperature

## *14.6.5 Personal Adaptation*

Arguably, one of the most immediate ways to adapt to an indoor environment is through *personal* adaptation using clothing (e.g., putting on a jumper). Although other personal adaptive opportunities arise (e.g., switching on a small electric fan-heater), clothing appears the preferred choice (Brager and de Dear 1998). In Liu et al. (2012a) study, clothing insulation level was quantified using a checklist provided in a questionnaire. Throughout most seasons, respondents in the north side offices generally wore more clothing than their colleagues on the south side offices, due to the lower temperatures. Figure 14.7 demonstrates how clothing insulation values vary with indoor air temperature by season.

The authors argue that: "occupant adaptation will not only depend on the outdoor air temperature but will also be affected by the local culture, people's habitats, and expectations. In Chongqing, China, with its extreme hot summer and cold interclimate, people have greater adaptability in terms of physiology, behavior, and psychology, to produce a mid-comfort temperature range. In such a context, the application of the ASHRAE adaptive comfort zones would be inappropriate without modification. The indoor thermal environments are severe, both in summer and winter, without any mechanical heating and cooling systems. Under such thermal conditions, occupants tended to shift their psychological expectations to a greater extent, compared with conditions with offsetting impacts". The study thus shows that a combination of adaptive responses is necessary to achieve thermal comfort in some instances.

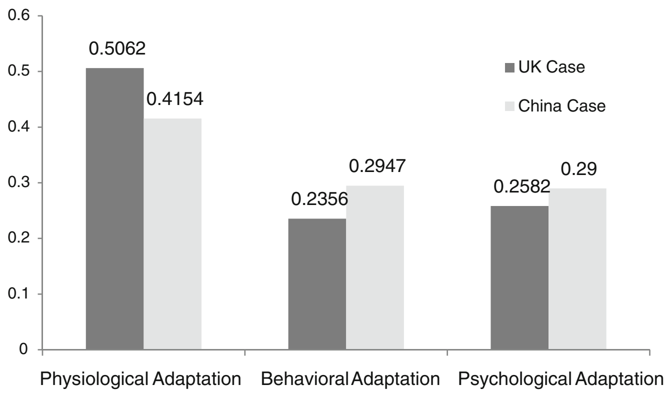


**Fig. 14.8** Weightings of three categories of adaptation

### *14.6.6 Delivering Acceptable Environments*

In order to deliver indoor environments that occupants find thermally comfortable, considering all the complexities previously discussed, it is worth noting the following.

Liu et al. (2012a) find that physiological adaptation is the most important type of adaptive class when occupants are faced with having to achieve thermal comfort (Fig. 14.8). While psychological and behavioral adaptations are of similar importance, cases may vary depending on individual circumstances. The authors conclude that occupants can generally achieve thermal comfort in buildings if: (1) personal preferences are taken into account (which stem from culture, habituation, and socioeconomic backgrounds); and (2) there are person-oriented adaptive opportunities (e.g., use of window blinds). As previously mentioned, occupant's needs are more important than the capabilities of the technology in the building. If environments fail to provide desirable thermal conditions and adaptive opportunities, then 'work-around' solutions invariably arise, which can defeat the aims of energy efficiency.

## 14.7 Energy Management Systems

It is well known that occupants are responsible for significant variations of energy consumption in similar households. Managing indoor environments can be: undertaken manually (e.g., pushing light switches); fully automated, whereby control is 'taken' from occupants; or a meeting of the two. A dichotomy arises whereby a building's energy use is jeopardized if occupant control is too limited; yet if control is maximized, occupants can be overwhelmed by the required interaction necessary to maintain optimal comfort while minimizing energy use. This is a complex issue to resolve in both domestic and nondomestic buildings.

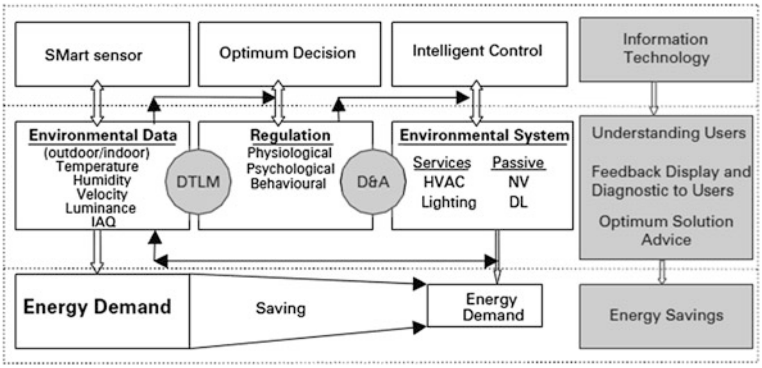


**Fig. 14.9** SMODIC intelligent building energy management system model *Note IAQ* Indoor air quality, *DTLM* Dynamic thermal comfort and lighting model, *D&A* diagnostics and advice, *HVAC* Heating ventilating and air conditioning, *DL* Daylighting, *NV* Natural ventilation

When considering *energy* and *intelligent buildings of the future*, an image is often conjured up that features a slick, centralized energy management system. It may have complete automation and control over the building, part control, or simply advise occupants. It might function through a dedicated interface, or operate through a simple home PC or laptop. Yao and Zheng (2010) present such a model for an intelligent building energy management system to control the indoor environment. They present a holistic, integrated, building energy management model called *'Smart-sensor, Optimum Decision and Intelligent Control',* or SMODIC (Fig. 14.9). It takes into account occupants' responses to their indoor environment using an optimal decision-making process, based on multiple criteria facilitated by the Dempster-Shafer Theory (Dempster 1968; Shafer 1976), to advise occupants what actions to take. The SMODIC model combines information technology and person-centered concepts for maximum effect.

The system has three main subsystems: (1) a wireless sensor network, which can detect: air temperature, radiant temperature, air velocity, humidity, air pressure, and air quality, in addition to lighting, acoustic variation, $CO_2$ concentrations, and cleverly—occupant preferences; (2) an optimum decision system which analyzes multiple factors influencing comfort and energy consumption; and (3) an intelligent control system which realizes the optimum control through transmitting the passive and active solutions to actuators.

### *14.7.1 Energy Feedback Displays*

The area of *energy feedback displays* is a relatively immature technology within the building services industry. There are very few commercially available products which manage indoor environments from a holistic perspective such as the


**Fig. 14.10** Home energy display meter

SMODIC model describes (Yao and Zheng 2010). However, there are energy management systems that monitor power in commercial buildings like supermarkets and factories. These tend to highlight how building services can best operate in response to dynamic changes ‘on the ground’.

Toward a more basic approach to energy management, is the use of feedback display systems. Driven by the UK carbon emission reduction target (CERT) (DECC 2006), UK energy suppliers have an obligation to reduce domestic carbon emissions. One strategy adopted was to issue customers with free energy display monitors (Fig. 14.10). The displays inform users how much energy they are consuming, how usage compares to previous days, energy costs, and other variables (e.g., time and temperature). Such devices have a limited impact. This could be due to instances where occupants do not understand the display, the electricity clamp meter fails, or the display is no longer used. Wood and Newborough (2003) evaluated the impact of energy consumption indicators on household cooking appliances in 44 UK households. They found that average consumption decreased by 15 %. A similar study conducted in the Netherlands (van Dam et al. 2010) showed that use of home energy monitoring systems resulted in a 9 % decrease in energy use and concluded that energy saving behavior is habitual and cementing new habits takes time.

Presently on the market, is a slightly more advanced Web-based feedback product called *AlertMe* (AlertMe.com Ltd 2011). The product (in 2012) includes a clamp-on electricity meter, an online hub, a visual display unit, and the option of adding smart-plug that monitor individual appliances. Again, feedback information is generated for users to act upon, facilitated by a ‘clean’ user interface, available in formats for home PCs and mobile phones. Such products are relatively new. Undoubtedly, more products will come onto the market in the near future, offering increased functionality and capability.

### *14.7.2 Data Mining*

Energy feedback displays or energy end-use models used for supply and demand issues (Lim and Yao 2012), often process large quantities of data. Furthermore, application of wireless sensor networks (Yao and Zheng 2010) requires efficient data handling, if they are to be integrated within safety products. Although instrumental, data generated by sensor networks can be very noisy (i.e., they contains anomalies, blank entries etc.). Therefore, dealing with data 'noise' in order to facilitate decision making processes is crucial for fire evacuation and air pollution management.

Data mining, defined as: '*the non-trivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data*' (Fayyad et al. 1996), is a way to deal with noise. The techniques are generally classified into two areas: *predictive algorithms*, which build mapping functions between input and output functions (e.g., to predict the temperature given a particular day and location); and *descriptive algorithms* which search for patterns and associations in data (e.g., clusters and patterns in databases for modeling). Both can be used for real-time analysis and in attempting to predict 'occupant behavior' or establish relationships between 'behavior and energy consumption'. Wu and Clements-Croome (2007) discuss a method of handling sensor data whereby they use: simple cleansing procedures to remove invalid data; the K-means clustering algorithm to detect outliers; the Pearson correlation coefficient to determine variables relational strength and averaging and weighted averaging techniques to fill missing data records. The steps they employ reduce the data quantity from 2,313,682 observations to 750,148 useful entries. Such methods are required for sizable datasets if *useful* data are to be extrapolated for use in indoor environmental systems and POE.

## 14.8 Building Performance Assessment

Quoting Peter Drucker : *"If you can't measure it, you can't manage it"*, tells us much about the need to assess and measure indicators in order to manage business. Buildings are no different. In the nondomestic context, 'building performance' refers to indicators such as: (1) *energy consumption*; (2) indoor environmental quality (IEQ) (e.g., air quality, light, noise, temperature (thermal comfort), humidity conditions, and esthetics); (3) *water use*; and (4) *waste management*. Measurement and analysis of such indicators can provide support when planning strategic goals for financial, environmental, and organizational benefit—occupants included. Increasingly, organizations need to conduct performance assessments, as increasing priority is placed on energy and environmental conservation. But how is this done?

Standardized methods to assess building performance began to emerge during the 1970s (Socolow 1978), with commercial buildings receiving more attention during the 1980s and 1990s. Nowadays, standardized methods have been developed for: (1) the UK, by the *Chartered Institution of Building Services Engineers—TM22* (CIBSE 2006); (2) Germany, by the *Association of German Engineers—VDI 3807* (VDI 2007); and (3) the US, by the American Society of Heating, Refrigerating and Air-conditioning Engineers(ASHRAE 2007)—*Standard 105-2007*. These methods offer basic, intermediate, and advanced levels of calculation, each with different strengths and weaknesses.

Benchmarking is a valuable method of energy assessment and comparison. Different metrics (e.g., kW h/m$^2$/year, W/m$^2$/year) exist for buildings within numerous sectors (e.g., schools, hospitals, offices, etc.) and can be used to obtain approximations in the context of compliance for building codes and standards. It is noted that factors such as *occupant density*, *occupancy level*, appliance ownership, and climatic variation are all beyond the control of building operators in some instances. In response to this, performance assessments incorporate a *normalization* procedure within methodologies to account for such variables.

Alwaer and Clements-Croome (2010) present a method for determining the relative importance of key performance indicators for assessing intelligent buildings using the analytical hierarchical process (AHP) for multi-criteria decision making. From a list of 115 possible performance indicators, 11 actors within the industry were asked to rank them into four groups: mandatory, desired, inspired, and nonapplicable. Indicators were based on whole life (building) modeling; hence they were based on *people*, products, and processes. The authors state that: *'the priority levels for selected criteria is largely dependent on the integrated design team, which includes the client, architects, engineers, and facilities managers'*. This was problematic as these professional backgrounds have a different perspective on what constitutes 'good performance'. A tool is developed from the model (SuBETool) which is better geared toward comparative analysis rather than identifying an absolute outcome.

Different studies, such as Wong and Jan (2003), look into specific assessment areas. The work attempts to measure, objectively and subjectively, how effective a Singaporean classroom environment is (in terms of thermal comfort, space, air quality esthetics, noise, and build quality) on learning. Interestingly, from the six indicators, esthetic and space considerations appeared the most important; followed by air quality, thermal comfort, noise, then finally build quality. In some instances, subjective and objective outcomes conflicted. For instance, people perceived themselves as 'uncomfortable' (subjective), although temperatures were within 'acceptable' limits (objective). This highlights the human dimension to how environments are perceived. Arguably, the type of activities occupants engage with can have a significant impact on how environments feel, which consequently impact upon how they behave.

## 14.9 Conclusion

This chapter demonstrates the growing need to better understand the inextricable link between occupant behavior and building performance. The opportunities to impact on energy use are wide ranging, delineated by a building's energy end-uses and their associated systems (e.g., heating, appliances etc.,) and control mechanisms. POE and use of wireless sensor networks can facilitate the understanding of occupant behavior and provide valuable feedback loops to industry. Removing the social, managerial, and technological barriers that stifle energy efficient behavior are prerequisites to ensure that building performance is maximized. Indoor environmental quality is also essential when creating spaces that are functional with pleasing esthetics, comfortable, promote wellbeing, and bolster work output. Methods of measuring work productivity and thermal comfort can be implemented to gage the relationship between people and buildings. Occupants adapt to their environment through physiological, psychological, and behavioral reactions; further, the need for adaptive opportunities and level of indoor environmental control are also fundamental in creating synergy between buildings and its occupants. Energy management systems can aid or hinder the way buildings are operated, but are not free from sociotechnical issues either. Ultimately, occupants' needs override those of technology and the physical constraints of buildings, as demonstrated by the 'energy performance gap' that emerges when buildings are assessed using standardized methodologies for reporting on building energy consumption. Toward the future, building performance and occupant behavior will be more aligned, supported by technological innovation and gradual changes of attitudes in energy usage.

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# Chapter 15
# Facilities Management

**Edward Finch and Xiaoling Zhang**

**Abstract** This chapter explores the discipline of facilities management and the contribution that this emerging profession makes to securing sustainable building performance. It argues that the realization of intended environmental improvements depends pivotally on the behavior of users and the on going management of the facility throughout its life. The chapter describes an alternative view of a building's evolution as seen through the eyes of the facilities manager. In doing so, it highlights a much greater diversity of opportunities in sustainable building design that extends well into the operational life. *Learning scope*: on successful completion of this chapter, readers will be able to: (1) demonstrate the role of facilities management in ensuring continued performance improvements with respect to sustainable objectives; (2) explore buildings as a multilayered process rather than a product; (3) explain how facilities managers consider sustainability interventions at critical points within this layered life cycle; (4) examine how whole life building economics impinges on sustainable decision making.

**Keywords** Facilities management · Sustainable building design · Sustainable building technologies and management

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## 15.1 Introduction

The concept of sustainable buildings continues to attract international attention in the wake of growing environmental demands. Much of the focus has been on the accommodation of sustainable principles in building design and the incorporation of retrofit solutions in the subsequent building life cycle. A fixation with technological remedies can, however, overlook the fundamental role of the facilities management team in ensuring the continued rectification and improvement of a building's performance. The idea of a sustainable building should not be one of a 'product' but a 'process' subject to continuous improvement throughout its life. Much has been discussed about the failure of many 'sustainable' buildings to realize their energy saving potential. This failure in performance may arise at handover or may be evident over time as a general deterioration in performance. In this chapter, we consider 'sustainable buildings' as just that—buildings that achieve high levels of performance, not just from day one, but throughout the building's life. To achieve this, facilities management (FM) plays an indispensable part, tackling the complexities of people, process, and place. In this chapter, we consider the type of sustainable technology that can be used to leverage energy savings. The chapter discusses the vital importance of decision-making cycles that reflect the life of the building and the systems within it. The layered concept of building systems and the associated concepts of passive and active systems highlight the staged involvement of the facilities management team.

The discipline of facilities management is a relatively new, yet largely misunderstood profession. At the heart of this role is the capacity to integrate. In the face of increasingly complex building systems, a greater diversity of user involvement and an aversion for operational risk, facilities management must attempt to resolve conflicts and identify synergies. It is perhaps no coincidence that the Portuguese word 'facilidade' or the Spanish word 'facilidad'—the translation of 'facilities'—means 'ease' or 'easiness'. The idea of 'ease-of-use' is fundamental to the facilities management role. Yet, in the context of sustainability, with the headstrong desire to embrace new technology, the management challenge of making solutions accessible and appropriate is often overlooked.

The emergence of facilities management tells us something of its modern day role in supporting sustainability issues. The unprecedented need for integration in facilities today can be traced to the advent of two developments in the 1970s. The first of these was the introduction of computers and IT equipment in the office environment, which in turn presented challenges in relation to wiring, lighting, acoustics, and territoriality. The second of these developments was the innovation of systems furniture or "cubicles". While attempting to provide a technological 'fix' to the IT challenge, cubicles presented new questions of their own: not least of which was who would take responsibility for procuring and managing such environments? The need for an integrating professional led to the development of the professional association 'International Facility Management Association' in 1981 that has since spawned other professional associations worldwide.

## 15.2 Definition and Roles

The term 'facilities management' (FM) has been the subject of much debate since its conception. Leaman (1992) suggests that "facilities management brings together knowledge from design and knowledge from management in the context of buildings in everyday use". He continues, remarking on the apparent differences between designers and modern day facilities managers. *"The management (FM and Property Management) disciplines—which are less well-defined as disciplines, but include maintenance, administration and financial management—tend to be much more short term, often day-to-day, in outlook. They deal with shorter timescales, the project deadline, the end-of-year financial statement, the quarterly report, the immediate crisis*".

In opposition to this short-term position, Thompson (1990) argued for a more strategic view of the discipline, arguing that "real facilities management is not about construction, real estate, building operations maintenance, or office services. It is about facility planning—where building design meets business objectives".

A recent definition of FM places less emphasis on the built asset, focussing instead on the role of service provision in a support capacity. The European CEN definition of facility management is expressed as: *'the integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities'* (CEN EN 15221-1).

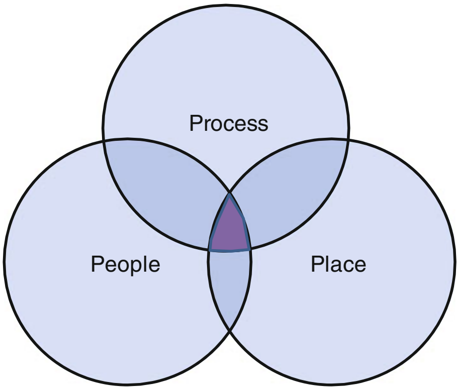
This definition makes no explicit reference to building operation. In so doing, it appears to bypass the role of the built environment in determining service outcomes. Moreover, it does not attempt to acknowledge the requisite skills of the property professional in meeting these outcomes.

Perhaps the definition that has had the greatest longevity is that of the international facilities management association (IFMA): *'Facility management is a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process, and technology'* (International Facility Management Association 2009).

Figure 15.1 shows this triumvirate view of FM, bringing together people, place, and process. Technology provides both an enabler and a challenge in this context. From a sociotechnical perspective, it is the combination of management skills and suitable technology that dictate building and end-user performance.

In professional practice, it is often seen as sufficient to describe the role of FM in terms of the scope of FM services provided. This can encompass an expansive range of services, including security, cleaning, maintenance, catering, landscaping, hygiene, health, and safety, all of which have a bearing on the sustainability agenda. However, a definition that is framed in terms of work packages provides no clarity as to the value adding proposition of FM. In contrast, the emphasis on the 'integrating' role of FM identified in the IFMA definition captures the essence of FM as a discipline. Innovations such as bundling of services, performance measurement, and multitasking are illustrative of integration approaches.

**Fig. 15.1** The facilities management triumvirate




## 15.3 Energy Operation and Management

It is useful at this point to consider the economic impact of FM and maintenance management. Yiu (2007) laments on the tendency to focus on design improvements as a means of improving the environmental, and hence economic return of buildings: *"Most studies focus on new designs that encourage more efficient use of natural resources, deliver pollution free and ecologically supportive urban landscape. When economic development is addressed, most focus on the increase of property value by these new designs. Unfortunately, there is very little discussion on the contribution of maintenance of existing buildings to sustainable development and those exceptions focus on environmental issues only"* Yiu (2007). In his study of the Hong Kong residential market (using sensitivity analysis), it was suggested that a 10 % reduction of housing depreciation could yield a 14 % increase in gross domestic product (GDP) in a decade, while costing only about 2.3 % of GDP. Such figures resonate in other parts of the global property market and reinforce the argument that FM has a key role to play in sustainability targets and in delivering real financial returns.

### *15.3.1 Active Versus Passive Solutions to Building Operation*

Sustainable technologies can be categorized under two broad headings: *active* and *passive* design. Passive design refers to building design solutions which do not require mechanical equipment for heating, cooling, ventilation, or daylighting. Their environmental performance is instead, determined by the characteristics of the building envelope (orientation, air permeability, exterior walls, doors, windows, and roofing), which in turn determine solar loss and gain. By careful specification of these design parameters, energy consumption and lifetime costs can be significantly reduced. The alternative, active design, refers to the use of artificial, mechanical, or electrical sustainable technology to control, heat, cool, or light a space (supporting air conditioning, lighting, vertical transportation, pumps, and fans among others) (Kibert 2008). A recent report published by Mikler et al. (2008) has itemized the major passive sustainable elements that influence energy consumption. These are summarized in Table 15.1.

**Table 15.1** Passive design elements/technologies (adapted from Mikler et al. 2008)

| Passive design elements/technologies | Function category of the passive design elements/technologies |
|---|---|
| Buffer spaces and double facades | Passive heating<br>Passive ventilation |
| Orientation | Passive heating<br>Passive ventilation |
| Building shape | Passive heating<br>Passive ventilation |
| Space planning | Passive heating<br>Passive ventilation<br>Passive daylighting |
| High-performance windows (clear, low-e) | Passive heating |
| Window size and placement (window to wall area ratio) | Passive heating<br>Passive ventilation<br>Passive cooling<br>Passive daylighting |
| Operable external shading | Passive heating<br>Passive cooling |
| High-performance insulation | Passive heating |
| Thermal mass | Passive heating<br>Passive cooling |
| Minimized infiltration | Passive heating |
| Strategic architectural features | Passive ventilation<br>Passive daylighting |
| Openings to corridors and between otherwise separated spaces | Passive ventilation |
| Central atria and lobbies | Passive ventilation |
| Wind towers | Passive ventilation |
| Nocturnal cooling | Passive cooling |
| Stacked windows | Passive cooling |
| Passive evaporative cooling | Passive cooling |
| Earth-tempering ducts | Passive cooling |
| Interior surface colors and finishes | Passive daylighting |
| Light shelves | Passive daylighting |
| Skylights and light tubes | Passive daylighting |
| Clerestories | Passive daylighting |

### *15.3.2 Layered Building Systems*

The duality of passive versus active design conceals a more complex scenario in relation to facility decision making. The *layered* building system model (Duffy 1974) further explains buildings as complex systems. This model expresses the dynamics of buildings: seeing buildings as an ongoing process of evolution rather than being a one-off event. The model is instructive in relation to the sustainability agenda for several critical reasons:

- It identifies the opportunities for sustainable interventions within several life cycles of differing periodicity;
- The building *shell (skin and structure)* itself is the most long lasting and intractable element of the decision-making process;
- Enclosed within the building shell, are several building systems (*services* (M&E), *scenery,* and *settings*), all of diminishing life cycle;
- Shorter life elements offer more frequent opportunity for change, while at the same time highlighting their increased cost significance (as such elements may be replaced several times throughout the life of a building).

This decision-making framework has profound implications for sustainable building design, identifying as it does, the key role of FM. It also articulates the 'softer' elements of facilities that have an increasing significance in terms of cooling and heating loads.

Figure 15.2 identifies the key layers of a building's evolution expressed in relation to decision-making junctures. Instead of a simple dichotomy between 'new-build' and 'retrofit', the diagram differentiates at a more granular level the dynamics of a building. Each layer defines a discrete building life cycle that is distinct from each neighboring layer. The layers range from the longest life cycle corresponding to the building structure (25–75 years) to the innermost layer with a lifecycle that is realized on a day-to-day basis (corresponding to the 'set').

The diminishing size of the layers from shell to set (Fig. 15.2) indicates the declining opportunity to create a sustainable solution that satisfies internal environmental requirements and at the same time obviates the need for a

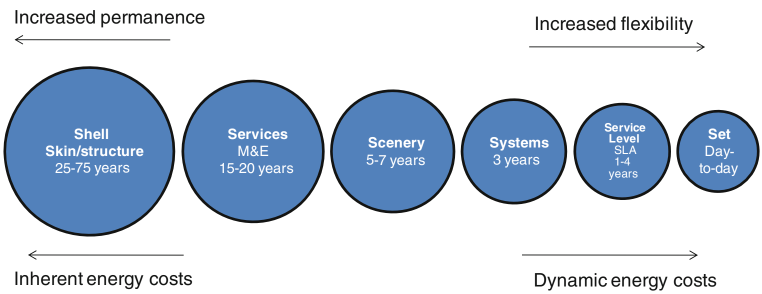



**Fig. 15.2** The layered decision cycles of buildings (*Source* Duffy 1974)

technological intervention. The design principle of ‘getting it right first time’ is uppermost in this approach, although the scarcity of newly build projects compared to the existing stock of buildings in most developed countries may force the decision maker to consider shorter life layers, particularly those post fitout (scenery, systems, service level, and set). The layers can be described, in order of decreasing life cycle as follows.

#### 15.3.2.1 Shell

This layer’s life corresponds with that of the building itself, lasting for 50 years or more. It incorporates both the *structure* of the building and the skin (cladding system and facades). Key design decisions such as height, size, depth, and orientation have intractable effects on the energy load imposed by the building. Well-designed building shells obviate the need for technological remedies (active systems), because they provide a stable, uniform, and near-optimal regime that only requires fine tuning. Emphasis at this layer corresponds to ‘passive’ solutions that do not require mechanical or electrical fixes.

#### 15.3.2.2 Services (M&E)

The mechanical and electrical (M&E) services layer represents part of the problem as well as part of the solution (or technological fix). Before the advent of energy awareness, M&E services were used liberally to make up for the deficiencies in the design of the building shell and skin. Modern solutions involving retrofits on a 10–15 year basis have to meet dual demands: satisfying human comfort conditions while optimizing energy usage. M&E services can exacerbate the problem of energy demand (e.g., heat gains and controls that are not localized). Decision making at this level corresponds to the introduction of ‘active’ solutions.

#### 15.3.2.3 Scenery

The fit-out stage of modern office environments involves the introduction of internal elements such as ceilings, partitions, and finishes. Typically, this stage corresponds to the point in time when a landlord would let out the facility. The tenant fits out the facility to meet the specific needs of the organization. The configuration of false ceilings, internal partitions, and choice of finishes can have a significant impact on energy consumption. Partitions that obstruct ventilation, disrupt cellular arrangements for air intake and exhaust diffusers, and prevent zoning may reduce building efficiency. This problem can increase over time as the original design intent of the M&E designer and structural designer fall into obscurity. Partitions and ceiling voids also affect lighting efficiency as shown by the early work of Ikemoto and Isomurai (1995).

#### 15.3.2.4 Systems

Information and communications technology (ICT) deployed in a building, typically undergo renewals every 3 years. Such systems embrace new generations of computing technology, which present differing challenges in terms of thermal load, temperature tolerance, noise, and lighting requirements.

#### 15.3.2.5 Service (FM)

This layer is absent from the original conception of the layered model. However, it is seen by the authors as a necessary addition, since the engineering of the service level agreement (SLA) and performance specification has an increasingly important impact on energy consumption. The duration of FM service contracts is variable (either in-house or outsourced) but are typically 1–4 years in duration with renewal options and allowances for change issues. The design of the SLAs in relation to maintenance, cleaning, lighting, etc., will impact on:

- The longevity of components (e.g., run to failure versus planned maintenance);
- The sourcing of sustainable building products that can be effectively cleaned and maintained;
- The facility's hours of use, both for service providers (cleaning, maintenance, and security among others) and for employees;
- The demand profile of the building and the level of tolerance for seasonal fluctuations;
- The requirements for 'always on' IT equipment.

#### 15.3.2.6 Set

This final internal layer is realized on a day-to-day basis. It represents the extreme 'soft' end of facilities management, with a close interaction with building users. The set includes flexible items such as furniture, fittings, and equipment (FFE) within the building. They may give rise to new, unanticipated challenges such as additional design loads or new environmental requirements.

Figure 15.2 highlights how the inherent or baseline energy performance of the building is prescribed once the location, structure, and skin of the building is chosen (passive elements). This energy load might be described as the 'inherent' energy load. As we consider layers and systems of decreasing life cycle, their design typically reflects a response to change issues, including seasonal changes in external temperatures, daily fluctuations, changes in use, changes in occupancy, and changes in thermal load brought about by new systems (e.g., heat gains produced by computing systems).While this represents a rational approach to the design sequence, poor design decisions at the early stages of structure and services leads to a very different outcome.

The short life cycle elements that should be in place to deal with specific occupier needs are instead used to make up for the deficiencies of the original design. Similarly, in relation to retrofit, intractable decisions relating to the original building structure invariably necessitate a solution at the shorter life cycle end of the spectrum. Instead of satisfying the fine-tuning required to achieve flexibility, the shorter life cycle elements provide a costly remedy or 'fix' for an undesirable inherent baseline load. This is echoed by the research findings of Zhang et al. (2011a, b), which identified that passive design technologies are comparatively inexpensive to apply as opposed to active design technologies.

### *15.3.3 Sustainable Energy Efficient Technologies*

Increasing awareness of the environmental impact of building emissions has triggered a plethora of technical solutions designed to reduce such levels. At the industry level, facility managers seek to understand the impact of these sustainable (or low carbon) technologies and the most effective means to implement and manage them in the operational context. If managed properly, such low carbon technologies form the basis of reduced costs and reduced carbon emissions while providing a productive built environment. Built facilities can impact on the natural environment in many ways over their entire life cycles. Yeang (1995) lists four types of impact which built facilities have on global ecological systems and resources:

- The spatial displacement and modification of natural ecosystems;
- The impacts resulting from human use of the built environment, and the tendency for that use to spur further human development of the surrounding ecosystems;
- The depletion of matter and energy resources from natural ecosystems during the construction and use of the facility;
- The generation of waste output over the whole-life cycle of the facility that is deposited in, and must be absorbed by, natural ecosystems.

To date, various sustainable technologies have been incorporated in building designs as has been identified in previous studies (Glicksman et al. 2001; Parker 2004; DoE 2006). Zhang et al. (2011a, b) investigated how sustainable technologies themselves may contribute to the competitiveness of real estate developers in China.

There are various ways in which building energy consumption can be reduced and sustainability issues addressed. Such technologies can be classified using the following six layers as discussed: shell (including skin or facade), services (M&E), scenery, systems, service (FM), and set (see Table 15.2).

Table 15.2 Sustainable elements/technologies/systems categorized using the building layered model (adapted from Zhang et al. 2011a, b)

| Code | Sustainable technologies/designs/materials | Building layer | Passive/Active design strategy | Key references |
|---|---|---|---|---|
| $GT_1$ | Transparent insulation systems | Shell/skin | Passive | Wong et al. (2007) |
| $GT_2$ | Atrium design | Shell/skin | Passive | Sharples and Lash (2007) |
| $GT_3$ | Smart windows/facades | Shell/skin | Passive | Baetens et al. (2010), Kirby and Williams (1991) |
| $GT_4$ | Modular design, prefabricated concrete technology, and flatpack design | Shell/skin | Passive | Tam (2009), Noguchi (2003) |
| $GT_5$ | Innovative insulation materials | Shell/skin | Passive | Papadopoulos and Giama (2007) |
| $GT_6$ | Holistic/bioclimatic design | Shell/skin | Passive | Lam et al. (2006) |
| $GT_7$ | Structural insulation design | Shell/skin | Passive | Goodhew and Griffiths (2005) |
| $GT_8$ | Shading devices | Services (M&E) | Active and passive | Guillemin and Molteni (2002) |
| $GT_9$ | Solar energy powered generating systems | Services (M&E) | Active | Ecotecture (2006) |
| $GT_{10}$ | Solar energy heating technology | Services (M&E) | Passive | Ecotecture (2006) |
| $GT_{11}$ | Natural ventilation technology | Services (M&E) | Active | U.S Department of Energy (2009) |
| $GT_{12}$ | Environmentally friendly materials for HVAC systems | Services (M&E) | Passive | UNEP (2003) |
| $GT_{13}$ | Integration of natural lighting with artificial lighting technology | Services (M&E) | Active and Passive | Ne'eman (1984) |
| $GT_{14}$ | Ground source heat pump technology | Services (M&E) | Active | Doherty et al. (2004) |
| $GT_{15}$ | Personalized ventilation systems | Scenery | Passive | Melikow et al. (2002) |
| $GT_{16}$ | Unobstructed interiors and lighting efficiency | Scenery | Passive | Hadwan and Carter (2006) |
| $GT_{17}$ | Monitoring of trigeneration and combine heat and power (CHCP) plant | Systems | Active | Cardona and Piacentino (2003) |

(continued)

**Table 15.2** (continued)

| Code | Sustainable technologies/designs/materials | Building layer | Passive/Active design strategy | Key references |
|---|---|---|---|---|
| $GT_{18}$ | Remote condition monitoring | Systems | Active | Yongpan and Zhang (2009) |
| $GT_{19}$ | Ambient intelligence | Systems | Active | Future Energy Solutions (2005) |
| $GT_{20}$ | Smart home systems | Systems | Active | U.S Department of Energy (2009) |
| $GT_{21}$ | Load monitoring | Services (FM) | Active | Norford and Leeb (1996) |
| $GT_{22}$ | Occupancy modeling | Services (FM) | – | Rabl and Rialhe (1992) |
| $GT_{23}$ | Outsourcing and gain sharing | Services (FM) | – | Fawkes (2007) |
| $GT_{24}$ | Energy performance contracting | Services (FM) | – | Davies and Chan (2001) |
| $GT_{25}$ | Product-service systems for office furniture reuse | Set | Passive | Besch (2005) |
| $GT_{26}$ | Embodied energy of furniture and fittings | Set | Passive | Treloar et al. (1999) |
| $GT_{27}$ | Office ergonomics and efficiency | Set | Passive | Brand (2008) |

## 15.4 Economic Appraisal

A key dilemma facing facilities managers is the conflict between capital costs and operating costs. More specifically, facilities managers often inherit solutions that have been selected on the basis of capital costs, neglecting the consequential operational costs. As a result, running costs are high and the costs of remediation are often higher. Buildings equipped with low carbon building technologies are commonly considered to be more expensive than conventional buildings entailing unjustifiable costs. Recent studies suggest that concern over the high costs of sustainable elements/design/technologies remains the primary barrier to sustainable building adoption. In a study of 700 construction professionals who responded to a survey by McGraw Hill (2008), over 80 % cited "higher first costs" as the main obstacle to sustainable building adoption.

### *15.4.1 Life Cycle Costing*

One of the most widely accepted methods used to evaluate the cost of sustainable building features is life cycle costing. This technique allows the calculation of a 'green premium' cost from a life cycle perspective, which arises from the increased construction cost (as opposed to extra design cost).The difference in life cycle cost between a sustainable design and conventional design represents the additional cost or savings that a sustainable building owner or resident can expect over the lifetime of a facility.

Life cycle costing includes both capital and operational costs that occur during the operational phase (e.g., utility costs, energy, water, maintenance, tax, and insurance) as well as future costs (e.g., refurbishment, maintenance, disposal/ recycling of materials).

A life cycle cost study by Goldstein and Rosenblum in 2003 considered the total development costs, interest payments, annual operating costs, and future replacement costs, when modeling the 30 years of life cycle costs for 16 sustainable projects and their conventionally constructed counterparts. On average, the 16 case studies showed a small "green premium" (incremental cost) of 2.42 % in total development costs, which were largely due to increased construction (as opposed to design) costs.

The research findings were echoed in the conclusions of another report (Kats 2003), in which several dozen building representatives and architects were contacted to assess the cost of 33 sustainable buildings from across the United States, compared to conventional designs for the same buildings. The average premium for these sustainable buildings is slightly less than 2 %, substantially lower than is commonly perceived. It has been summarized from Kats (2003) that the majority of cost premiums were a result of the increased architectural and engineering design time needed to integrate sustainable building practices into projects.

However, other research findings suggest an opposing view. For example, a more comprehensive study by Matthiessen and Morris (2004) suggested that location and climate are more important than the level of energy efficiency in determining ultimate cost. The survey looked at more than 600 projects in the 19 US states and examined the impact of location and climate on cost.

## *15.4.2 Barriers*

Despite the fact that sustainable technologies appear to have many advantages in the building sector, both in terms of cost-benefit savings (economic return) and in environmental benefit, it remains difficult to ensure that stakeholders in the construction industry take suitable action. A recent review of sustainable building activity found that only a very small proportion of England's building stock can claim to be sustainable (Williams and Lindsay 2005). The question arises as to why this is so?

Based on a review of previous work, Zhang et al. (2011a, b) summarized 10 barriers to the adoption of sustainable technologies in buildings as presented in Table 15.3. These barriers were previously identified in various studies (Tagaza and Wilson 2004; Williams and Dair 2007; The Energy and Resources Institute 2006) using different categories. Granade et al. (2009) summarized three types of barriers which hinder the implementation of energy efficiency technologies: (1) structural; (2) behavioral; and (3) availability barriers. The Carbon Trust (2005) also suggests a classification of these barriers into four main categories: financial costs/benefits; hidden costs/benefits; real market failures; and behavioral/organizational nonoptimalities.

The key barriers to sustainable adoption are further discussed below.

### 15.4.2.1 Higher Sustainable Appliance Design and Energy Saving Material Costs

The financial cost is usually considered as the critical barrier for those stakeholders who hesitate to invest in sustainable elements/technologies or not. A general perception is that the cost of using environmentally sustainable features is significantly higher than for traditional construction projects. Consistent with this point, in a 2009 joint survey of facility managers by the IFMA 2009, 63 % of respondents cited either capital availability, payback period, or return on investment as the top barrier to achieving energy efficiency for buildings. If additional construction costs do arise, how can we mitigate this conflict of interest? Who is willing to pay this extra cost? Some consumers, such as low-income households and small businesses, have limited access to credit, face high financing costs, and often have difficulty paying the life cycle costs for applying sustainable elements/design/technologies (Brown et al. 2008).

**Table 15.3** Summary of barriers influencing adoption of sustainable technologies (Zhang et al. 2011a, b)

| Code | Barriers | Key references |
|---|---|---|
| $BX_1$ | High perceived cost of sustainable design and material investment | Williams and Dair (2007), Tagaza and Wilson (2004) |
| $BX_2$ | Insufficient policy implementation efforts | Osmani and O'Reilly (2009) |
| $BX_3$ | Technical difficulty during the construction process | Tagaza and Wilson (2004) |
| $BX_4$ | Risks involved arising from different contact forms of project delivery and changed site practices and behaviors | Tagaza and Wilson (2004) |
| $BX_5$ | Lengthy planning and approval process for new sustainable technologies and recycled materials can be lengthy | Tagaza and Wilson (2004) |
| $BX_6$ | Lack of knowledge and awareness to the sustainable technologies | The Energy and Resources Institute (2006) |
| $BX_7$ | Lack of integrated efficiency for the building regulations and byelaws within the sustainable framework | The Energy and Resources Institute (2006) |
| $BX_8$ | Lack of motivation from customers' demand | Osmani and O'Reilly (2009) |
| $BX_9$ | Unfamiliarity with sustainable technologies makes delays in the design and construction process | Eisenberg et al. (2002), Tagaza and Wilson (2004) |
| $BX_{10}$ | Interests conflicts between various stakeholders in using sustainable measures | Williams and Dair (2007) |

#### 15.4.2.2 Insufficient Policy Implementation Efforts

Another challenge for the sustainable elements/design/technologies is inadequate policy implementation efforts. It is generally understood that most project managers on-site are risk averse: they are not willing to run the risk when there is insufficient policy or regulation at hand. In this context, it is considered that the guidance and commitments from the government can drive and motivate contractors to adopt sustainable elements/design/technologies. For example, by providing expedited permits, mandates and grant policies, density and tax incentives, affordable housing bonuses, and public recognition, the developers can enjoy benefits and mitigate barriers where sustainable housing projects are developed. It is also clear that regulations that support inappropriate tariffs can restrict interest in energy efficiency from the private sector.

#### 15.4.2.3 Lack of Motivation from Demand Side

There is a lack of appreciation by customers' demand side of the long-term cost savings, which is particularly evident in the residential sector, where builders/developers are slow to accept the associated social and environmental benefits of sustainable building practices. Consumers play an important role in accepting sustainable building technologies. They are not necessarily aware of energy demand for either individual sustainable appliances or total use. They may not regard energy efficiency or resource management as a high priority. It is obvious that the lack of motivation from customers is commonplace in a climate where the sustainable market is still in its infancy. This phenomenon can be described as "bounded rationality" according to Simon (1960), who argues that human beings act and decide only partly on a rational basis. In this context, a culture of social responsibility among buyers is increasingly sought.

## 15.5 Technologies and Management

Despite the apparent challenges of overcomplexity in modern buildings, technology has a key role to play in supporting the FM objective of increased environmental performance. Such tools furnish the facilities manager with much needed data in order to reconcile the 'hoped for' building performance, with the actual building performance. Among these technologies are:

- Computer-aided facilities management (CAFM);
- Building energy management systems;
- Automated identification (bar coding and radio-frequency tagging (RFID);
- Intelligent control systems;
- Intelligent buildings.

### *15.5.1 Computer-Aided Facilities Management*

Computer-aided FM (CAFM) has undergone a revolution in the last two decades. It emerged in the 1980s as a tool capable of linking graphical information (CAD) with nongraphic information (databases). Being CAD-driven, it enabled the facilities planner to attach information on fixed and movable assets such as luminaires or furniture systems to spatial entities such as rooms, department boundaries, or furniture systems (Teicholx 1995). The resulting integrated system provided a significant planning, forecasting and reporting capability, allowing the system to pass area information from the CAD environment to an inventory (database) and the reciprocal passing of information from a database to allow the

**Table 15.4** Facilities management IT tools and techniques

| Layer | Facilities management responsibilities | Decision/control tools |
|---|---|---|
| Site | Long range and annual facility planning<br>Real estate acquisition and/or disposal | Strategic decision making e.g., Sustainable transport policy; bio-climate, orientation<br>Decision support system (DSS) |
| Shell | New construction and/or renovation | Long-term budgeting<br>Decision support system (DSS) |
| Services | Architectural and engineering planning and design | Medium-term budgeting<br>Building information modeling (BIM) |
| Scenery | Work specifications, installation and space management | Short-term inventorizing<br>Computer-Aided Facilities Management (CAFM) |
| Services (FM) | Maintenance and operations management<br>Helpdesk systems | Regulatory management system (e.g., Health and Safety)<br>Facilities management information systems (FMIS) |
| Set | Telecommunications integration, security and general administrative services<br>Building management systems | Regulatory (day to day) control systems<br>Intelligent buildings<br>Automated data capture<br>Sensors<br>Wireless systems<br>Data mining |

population of CAD floor plans. Added to this were various space planning and optimization tools that yielded ‘stacking’ and ‘blocking’ plans that took account of organizational requirements (e.g., proxemics) within spaces.

Modern day CAFM describes a much broader church of modular capabilities that attempt to meet the demands of facilities managers and their customers. These vary from being CAD-driven, others database driven and yet others driven by parametric object-oriented models (Building Information Models). They also differ in the level of decision maker intervention ranging from strategic decision support systems (DSS) to automated real-time building management systems (BMS). Advances in networking, web interfaces, and open systems, means that such systems are amenable to many stakeholders, impacted by the FM role. Instead of being a closed box accessible only to the FM professional, a far greater level of transparency, and thus accountability and engagement is possible.

Some of the key capabilities of CAFM and the extended range of DSS are listed in Table 15.4. The table qualifies the particular FM activity (categorized by building layer) in relation to its potential impact on energy saving and sustainability issues. Much of the current focus in the literature is on the ‘regulatory systems’ that can be utilized in more sophisticated ‘intelligent buildings’. However, Table 15.4 identifies major opportunities for sustainable operation that arise much earlier in the decision-making process. As such, the tools to support these layers, while not amenable to automation, offer a greater opportunity for impact. Using an extreme example, a decision tool that enables the elimination of an underutilized facility in a portfolio, can have a far greater effect than any automated tool for regulating the energy performance of the building itself. Similarly, the choice of location (site) of a facility can have a longstanding and far-reaching consequence on travel plans of employees and consequent energy consumption arising from car travel. The term ‘budgeting’ used in the table refers to both ‘space budgeting’ and ‘financial budgeting’. These in turn can be viewed as being directly linked to the ‘energy budget’. Thus, a reduction in space requirement directly impacts on the associated cleaning, maintenance and operational costs, and associated sustainable impact.

Emergent features of modern day CAFM are: (1) interoperability; (2) incorporation of capabilities that are not CAD-driven; and (3) embracing of Building Information Modeling (BIM) object modeling capability.

### *15.5.2 Building Information Modeling and Data Warehousing*

The term building information model (BIM) is equivalent to the term *Building Product Model* (Fisher 1997) and derives from the work of Charles Eastman at Georgia Institute of Technology in the 1970s. It refers to a digital representation of the building process, enabling the exchange of detailed information by means of an interoperable data standard. While much of the development of this concept has been in the construction domain, it is now starting to have a significant impact on building operations.

In pursuance of improved energy performance of buildings, it is necessary to continuously gage the building’s performance with that of previous measurement, or against the original design. Such comparisons need to encompass the interests of owners, operators, and building users. The phrase ‘continuous commissioning’ has been used (Liu 2003) to describe this activity. However, this has only recently been possible with the advent of technologies such as data warehousing (DW). The exact demands of the data sources including a multitude of sensors and manual inputs related to maintenance, occupancy data, lighting, thermal comfort, and energy metering, make excessive demands on conventional database driven solutions. Added to this, is the volume of data now made available through wireless building automation systems. Ahmed et al. (2010) described how the use of ‘data warehousing’ provides a necessary advance from traditional use of databases to analyze building performance. In their research, they demonstrate the use of the ‘energy building information model’ (eBIM) which allows the integration of a BMS using the standardized building product and process modeling (Industry Foundation Class). As a result, their system provides a data aggregation and analysis tool, which could serve as a key DSS for FM processes. With the advent of wireless building management systems and the wealth of data that is now becoming available, such recent developments allow the concept of BIM to move from being a design tool to one that is capable of enhancing FM decision making.

### *15.5.3 Building Energy Management Systems*

The term building energy management system (BEMS) describes a computer-based control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems, and security systems. The integration of these systems allows the optimization of energy usage and comfort control. A BEMS consists of software and hardware; the software program being configured in a hierarchical manner can be proprietary, using such protocols as C-bus, Profibus. Increasingly, these systems are able to integrate each of the FM systems using Internet protocols and open standards. As such, they have become an invaluable tool in the facilities manager's armory in the battle against energy waste.

BEMS was first introduced in the 1970s, but have recently undergone a revolution on several fronts. Most of these advances reflect those that have taken place in the computer industry in general, related to the standardization of protocols, as well as the enabling of web functionality. Added to these more universal developments are some key accomplishments in the BEMS arena which include advances in:

- Intelligent building (IB) technology;
- intelligent control systems;
- sensor technology;
- the development of the concept of sentient environments;
- automated data capture.

Clarke et al. (2002) describe the concept of 'predictive control' which uses a simulation model to supplement measured building data. Simulation models are already used widely for the purposes of emulation, allowing BEMS operators to fine-tune control systems, train BEMS operators, and imitate fault situations. Such systems can also be used for fault-detection and diagnosis (FDD), enabling the detecting and location of BEMS faults. The novel concept described by Clarke et al. (2002) identifies a third application of simulation important to facilities managers: encapsulation within a BEMS system in order to provide simulation assisted control. The resulting system allows the FM to: (1) address cause and effect scenarios; (2) adapt to the impact of changing building use; and (3) provide better control through the calculation of interactions.

In a related study, Dounis and Caraiscos (2009) describe the use of a multi-agent-based control system (MACS) enabling user's preferences for thermal and illuminance comfort, indoor air quality and energy conservation. The development of such intelligent control systems represents a significant shift in the building control paradigm, such that they are no longer 'black boxes', but are now amenable to scrutiny by the FM team.

The explosion in the use of sensor technology presents many opportunities for building operations monitoring. This coincides with a time in the evolution of facilities management, where the procurement (contracting) process is starting to ask more exacting questions about building performance. As noted by Glazer and Tolman (2008): *'The contracting process becomes the determinant of the performance criteria, and delivery becomes a long-term fulfilment of these criteria'*. In essence, this statement identifies the increasing interaction between layers in the decision-making process. In particular, the 'services (FM)' layer, which is engineered around the *Service Level Agreement*, crucially depends on the feedback and learning opportunity of 'systems' used in the building.

## 15.6 Conclusions

This chapter has attempted to articulate an alternative view of a building's evolution as seen through the eyes of the facilities manager. In doing so, it highlights a much greater diversity of opportunities in sustainable building design which extend well into the operational life. By dispensing with the binary categorization of 'new build' or 'retrofit', a new set of intervention points become apparent. The chapter has emphasized, through the layered description of building systems, how the opportunities to exploit passive solutions at the early stage necessitate active solutions which are often more complex and difficult to manage. Invariably, these shorter life cycle elements involve greater complexity, greater FM involvement and greater cost to the environment. The judicious use of tools and techniques increasingly deployed by facilities managers can help in addressing both the intractable and the tractable decisions associated with these differing life cycle elements.

New developments in FM decision support tools present a major opportunity for the FM practitioner. The ability to capture significant amounts of data through wireless, open environments and through automated data capture could potentially overwhelm the decision maker at each stage of the layered decision cycle. However, it is envisaged that advances in data management (e.g., BIM, DW, and intelligent sensors) will offer up analytical tools which address this data mining challenge. Moreover, data will no longer be confined to simple 'black box' control systems. Instead, such systems will enable the removal of many barriers to sustainable technology adoption, both in terms of day-to-day performance and long-term financial return.

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# Chapter 16
# Information Management for Sustainable Building Projects

**Mingyu Yang and Andrew Baldwin**

**Abstract** This chapter explains why information management for sustainable building projects is essential. It reviews the concepts of modeling information flows and the use of *building information modeling* (BIM), describing these techniques and how these aspects of information management can help drive sustainability. An explanation is offered concerning why information management is the key to 'lifecycle' thinking in sustainable building and construction. The chapter also demonstrates how modeling information flow can benefit designers, highlighting the advantages it brings. It is argued that adoption of BIM considerably aids the staged processes, which are relied upon, to continually improve the delivery of sustainable buildings. It is only with this approach that all aspects of a building's construction and performance can be evaluated. *Learning Outcomes*: On successful completion of this chapter, readers will be able to: (1) appreciate information flows in the construction management process, (2) have a basic knowledge of BIM, (3) understand the role of technology in information transfer, (4) comprehend how integrated thinking impacts on the construction process, (5) discuss the benefits that BIM delivers in the context of sustainable built environments, (6) have knowledge of information flows in a building's life cycle and the comparative nature of BIM and traditional management models, and (7) gain insight into construction management science, and information and modeling technology.

**Keywords** BIM · Information flow · Information management · Modeling

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## 16.1 Introduction

*Sustainable Building* is a concept not only for the entire life cycle of the building product, but for the project process: from initial planning, through the stages of design, construction, usage and maintenance, to retirement, and demolition. It is a concept which extends beyond the perspective of product and time to include the integration of the stakeholder's involvement, the variety of professions, and the technological and management information systems required.

Requirement for 'green buildings' concerns more than just energy reduction, but instead, considers the *overall* environmental impact of the building product, including the selection of 'green' materials and the drive for 'zero carbon'. Embodied carbon dioxide assessments can now be built into the design process and construction methods can be accurately assessed. All these aspects require extended, efficient *information management systems*.

Modern organizations use a variety of resources in order to fulfill their business objectives. These include financial resources, skilled people, physical property, time, and information (Hinton 2006a); all these resources require careful management. How to effectively control and manage the information, the decisive element in the integrating and coordinating the construction project, is the key point for the success of any building project, and is particularly important for sustainable building projects.

The term 'information management' implies that information is a resource that can be managed (Hinton 2006b)—but what constitutes 'information'?

The concept of information is a subtle one of which there is by no means complete agreement as there is no universally agreed definition of terms 'data' and 'information'. Many different definitions exist. Nevertheless, Laudon and Laudon (1991) offer one, easily recognizable, workable definition: "Data are 'raw' facts, data are the basis from which information is shaped or formed by humans into meaningful and useful form". This is the definition which this chapter readily accepts.

While different definitions of the term *data* exist, what is universally agreed concerns the process of information management which comprises: gathering, analyzing, communicating, and storing it. Within a business organization, 'information management' is achieved through *Business Information Systems* that supports marketing, finance, human resource management, production, operations, and accounting practices.

In a construction context, Winch (2002) states that 'project management' encompasses two main categories of systems: *engineering information* systems and *enterprise resource management* systems. Engineering information management systems comprise of those required to the design the building (e.g., architectural systems, structural systems, mechanical and electrical services systems, etc.), while enterprise resource management systems include all those required to manage the project (e.g., accounting systems, payroll systems, estimating systems, etc.). At the interface of these two categories of systems, lies *Project Management Information Systems.*

The quality of information management during a construction project is vitally important. It has been estimated that 30 % of the cost of construction today is spent on gathering, entering, exchanging, and reentering data and information used by the different sectors involved in facilities planning, design, construction, operation, and maintenance.

There is a clear need for lifecycle thinking as a primary approach to sustainability in the building and construction sector. Actions with respect to building-purchase decisions, equipment or material use, and creating investments which trigger chains of events, all have impacts; not only within the building, but on the surrounding community and beyond. Such impacts have real and long-lasting consequences on people's wellbeing, the land, air, water, plants, animals, and generations to come. These in turn have consequences on the future of the building itself. Therefore the need for information management extends throughout the lifetime of the building.

## 16.2 Modeling Information Flow for Sustainable Building Projects

Information management is the most important element for project management in sustainable building. The production and flow of information in any sustainable building project is a complex system. Decisions made at each stage impact on subsequent stages including operation and even demolition. For example, decisions made at the conceptual and schematic planning phase (and the information produced), influences the detailed design phase. Information produced at the design phase will influence the subsequent construction phase. This is not a linear process. Information at the construction phase may: influence any remaining design; change client requirements; or demand the later construction process to be amended. Practically speaking, the information generation, transmission, and exchange is extremely complicated. Because of this complicated interrelation and inter-coupling of information, good construction information systems have the potential to fully integrate the construction project and all the parties involved. Unfortunately, the complex (information) relationship frequently leads to poor information management, misunderstanding among the project stakeholders, problems for construction administrators, conflict, and adversarial relationships. This diminishes the impact of project management, which in turn frequently leads to additional, unnecessary costs to construction. (Reports indicate that this is approximately one-third of the annual cost of American construction: approximately $600 billion is wasted.)

Therefore, there is a vital need within project management for a normative method for project administrators to precisely and explicitly describe the generation, flow, and exchange process of information. Such a method provides a basis for effective information exchange and a platform for collaboration. This scientific expression for such an approach is called *modeling*.

The modeling of data, information generation, and information flow (in construction) needs to clarify how information moves between the project partners and exerts its role in the construction project. Completion of any construction task is dependent upon physical resources (e.g., labor, plant, material, etc.) and its related information. In theory it is possible to decompose any project into many independent activities (tasks) and their related information requirements. The flow of information may be identified. On the basis of such structured thinking, the whole project can be shown as a large, interrelated network with thousands of task nodes and millions of information flows.

The accepted methods of modeling for project management purposes are based on critical path planning methods (Lu and Li 2003). These methods, first introduced in the 1950 s, have been developed over the last 60 years and now form the basis of all the recognized project management systems. They permit the modeling and forecasting of time and cost. They also allow resource allocation and optimization. This approach is well suited to modeling construction activities, but is ill suited to model information requirements because traditional critical path methods are unable to accommodate iterative links.

Other techniques better suited for information modeling include: entity-relationship diagrams; structure charts; data flow diagrams; role activity diagrams; the structured analysis and design technique; and *Integration Definition* for *Function Modeling*, (IDEF) diagrams (Newton 1996).

A key aspect of modeling is how to produce, operate, and maintain a large model for the benefit of the users. The process of identifying and solving a problem is a process 'from abstract to concrete', 'from superficial to essential' and 'from shallow to profound'. Modeling information requirements for a construction project typical produces a network of several thousand links. For such large network models to be easily understood and inspected for the continuity and integrity of information flow, the model needs a top–bottom hierarchical and interrelated structure, as shown in Fig. 16.1.
The general task of the project is at the top level as the beginning, the other tasks are decomposed hierarchically to the operative task featuring at the bottom. According to the internal and external relations of each task, a 'box' is used to represent the task content and scope. These boxes are not considered "solid", as they are 'black boxes'. Each 'black box' can be shown in greater detail by a more sophisticated model, and can be 'opened' by going down one level. In this way, upper work nodes of the upper and lower level model graph have a *parent–child* relationship; the single upper *parent node*, corresponds with the several lower *child nodes*. The scope of work and boundaries of the child nodes are defined by the parent node. Similarly, each child node can be further broken down and refined. In this way, the work node can be broken down level by level, until the level of detail provided, meets the required information management need. Ultimately, we can develop a complete hierarchical information flow model which can be used for practical project management.

In a practical engineering network, *work content* is delineated by *task nodes* which are relatively constant and unchangeable, but the specific content and

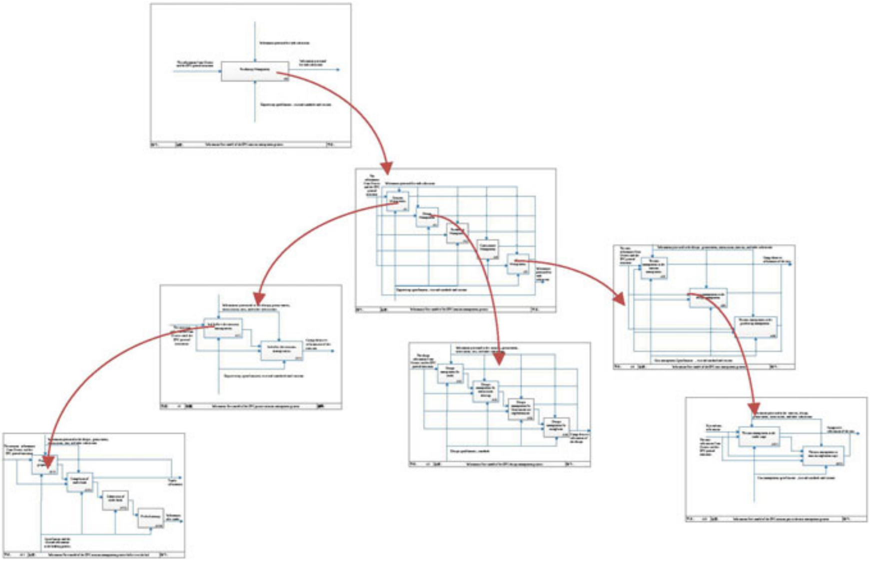

**Fig. 16.1** Diagram of a top–bottom interrelated hierarchy

delivery mode of information between task nodes can vary widely depending on project management style. Intuitively, different information management methods can directly influence the effectiveness of project management.

Through processing the information flow model, we can ensure accurate transmission of information between tasks. When information systems are used, information content achieves a higher degree of consistency and effectiveness during transfer processes. In doing so, this identifies the most effective information delivery mode and transmission path in order to facilitate useful information delivery to the right work node, characterized by its completeness, accuracy, and timely delivery. Then, by using optimization techniques such as *matrix modeling* (Austin et al. 1998), it is possible to eliminate or reduce the coupling relationship between tasks, and arrange task work order efficiently. In this way, the information management model not only clearly describes the complexity and entirety of the actual project, but allows for an efficient and orderly transfer of combined information between work nodes. It can also use information dependency to optimize work order within the task nodes attached to it. Eventually, by establishing and managing the model, the whole project will run in a scientific, economic, and efficient management mode.

Currently, integrated definition language (IDEF) modeling techniques are adopted in mainstream construction project information flow management models. After a series of developments, IDEF has become an IDEF series, including IDEF0, IDEF0v, IDEF3, and other variations on the basic system. Of these, the IDEF0 model system is widely considered to be the most suitable modeling techniques for building project. Users adopting IDEF0 can holistically describe function activities and their associations within the building system, and clearly comprehend a building system through development of a model.

Over the last decade there has been an increasing focus on improving information flow within the design process. This has emerged because of increasing recognition regarding the importance of design management with a backdrop of increasing modern building complexities, new forms of building procurement, and the continual need to reduce construction costs (Bjork 1992).

Modern design management includes: an effective briefing process; careful management of client requirements; and the use of new technologies, including virtual reality, to model both the construction product and the construction process.

At the conceptual and schematic design stages, the architect plays a key role in managing the design process. At these stages, focus moves toward the design deliverables, management control is exercised through the monitoring of the total man–hours expended; design evolves as an iterative process which reflects the creative processes architectural and engineering personnel. It is at the detailed design stage (sometimes termed the design production stage), that a more rigorous approach to design management and information flow is required. At this stage there are more 'stakeholders' and engineering disciplines involved, and more people engaged in related tasks.

Design is an iterative process. Therefore, traditional project management tools based on critical path planning and precedence planning techniques are ill-suited to manage detailed design and model the flow of information required to produce the design deliverables. New ways of working are required. One approach developed over the last decade and known as ADePT (Austin et al. 1999) is a highly structured approach that allows the user to define the design process, optimize the design process, produce project and departmental schedules, and enable performance measurement and reporting.

How can this approach be used in the context of sustainable design? First, any improved system efficiencies and reduced cost, aids sustainable construction. Second, a decision to develop a model of information flow and the resulting design deliverables provides a basis for the development of a 'sustainable' building information model. This assists the ongoing development of sustainable building construction by ensuring that all the elements of sustainable design are considered for each new building.

## 16.3 Building Information Modeling

Creating an information flow model that captures all the construction process activities is the basis of recognizing, integrating, and coordinating information and tasks between the various phases of building project. This combination of information integration and process integration is the key to achieving the complete integration of building systems. Information integration is the primary prerequisite for system integration. Modeling the information requirements cannot bring all the benefits required for truly sustainable building; therefore, in order to implement information integration and process integration throughout all the lifecycle phases of a building a new platform for information management is required. Building Information Modeling (BIM), provides such a platform.

BIM may be defined as: '*the tools, processes, and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction, and later its operation*' (Eastman et al. 2011). BIM is the action that provides an information model, a full digital expression of the building's physical and functional characteristics, providing architects, engineers, cost engineers, construction managers, and all other project participants with a comprehensive collection of information and knowledge to understand process and communicate simultaneously.

The concept of BIM is not new. For over 25 years the ability to develop models of the building product and utilize the data within these models for other applications has existed. Now, with new standards and improved interoperability of data between systems such modeling is becoming more commonplace and BIM is widely considered to be one of the most promising developments in the architecture, engineering, and construction (AEC) industries. Based on 3D modeling plus associated data and related 'rules' intelligent 'objects' may be created to provide the basis for a wider range of data analysis. These data, including non-geometric properties of the building unit such as material information, cost information, and equipment information may be used to model all aspects of the building and to simulate its operation, either directly or by transfer to other related modeling systems.

In the building information model, in addition to three-dimensional geometry model of building units, we can integrate other specification and performance data. The level of detail provided depends only on the amount of data attributed to each object. These data may be used to model all aspects of the building and to simulate its operation, either directly or by transfer to other related modeling systems, as in Fig. 16.2. Thus the building units are described as the 'multiple' and associated form.

Subsequently, if a project participant (e.g., architect) modifies the properties of a component unit, the building information model will automatically update the component, and this update always is associated with the other properties. Correlation between component properties not only improves the efficiency of cooperation between the project participants, but also assists in solving faults, incompatibilities, leakages, lack of details, and other issues concerning information production that result from unsynchronized design drawings. Production and use of the building information model operate throughout the project design, construction, operation, and management phases. Therefore, BIM provides reliable and shared knowledge resources for the entire life cycle of the building, from conception to disposal. It provides the participants in different building projects a good platform for data exchange and technical cooperation. For example, if a structural engineer changes the column dimensions of the structure, the column information in BIM model will be updated immediately; simultaneously, surveyors

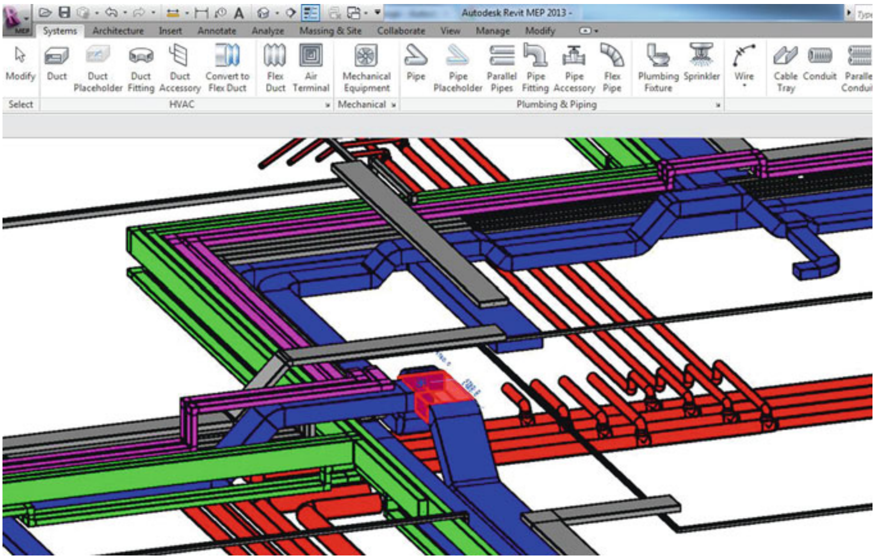


**Fig. 16.2** Integrated design base on 3D model

may adjust the labor and materials required to construct the columns according to the latest information; further, the construction team can arrange production timely according to the latest information. Therefore, the application of BIM will change the traditional, inefficient, adaptive, loose collaborative mode between building project participants, instead, establishing a unified, efficient, and sustainable building life cycle integrated collaborative mode, which is based on the network,

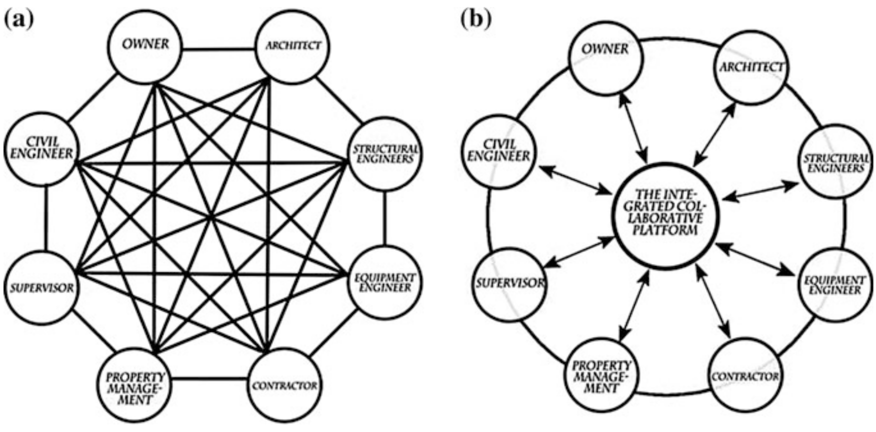


**Fig. 16.3** Project collaboration mode shift. **a** The adaptive and loose collaborative mode. **b** The shared integrated collaborative mode

with three-dimensional digital information model of the building components that carry all the features and functional properties as the only communication and collaboration platform (Li et al. 2005), as in Fig. 16.3.

## 16.4 The Application of BIM in Sustainable Building Design and Management

Following detailed research into the application of BIM technology, the architecture, engineering, and construction industry now seek to integrate other aspects (e.g., planning, design, construction, operation, removal phases) into a building information model to realize sustainable development within the whole building life cycle. To achieve this, research and application of sustainable buildings focuses on the following aspects.

### *16.4.1 Collaborative Design of Sustainable Buildings*

The collaborative design of sustainable buildings is multidisciplinary, multilevel, and multiiterative, undertaken with flexibility and openness. The amount of the data involved is very large, and the data has the complex meshed association and multiple definitions. In traditional architectural design and project management, information exchange between the design professionals and auxiliary systems, decisionmaking systems, expert systems which support design is carried out in a sequence manner. It cannot support the comprehensive, complex design data structures, and cooperative design, necessary for working in parallel.

By adopting BIM, the project establishes a fully functioning model that ensures a unique description of the building, a model that forms the basis for parallel design, and integrated information that covers the entire life cycle of buildings. At the same time, it also establishes unified design objects and the transmission and transformation of information for the entire project and provides professionals with design standards and a collaboration platform. Thereby, it can provide complete integration (e.g., construction data model, database schema, query language, conflict management, concurrency control, and consistency maintenance of the database state, etc.) under the heterogeneous data processing environment composed of different professions, hardware, software, operating systems, and databases within the design process. While interacting with a variety of auxiliary systems such as expert systems and decision support systems, sustainable building design teams can achieve timely communication, and full data sharing. It enables them to address an expansive range of issues including conflict control, data and knowledge reuse, and solutions for cooperative design work which draw together professionals working in different disciplines and physical locations. Only by working in these conditions will we realize the collaborative design of sustainable buildings.

### *16.4.2 Integration of Sustainable Building Design and Construction*

In traditional project management, building design, and construction is conducted separately, by different participants at different times. Although we can conduct various coordination and technical tests, shallow and low frequency communication cannot really solve problems and contradictions that may occur in the life cycle of a project. Meanwhile, a building's complexity and system integrity, together with the professional collaboration within the construction process, does not allow complete separation of design and construction. Therefore there is a management requirement for the integration of design and construction.

Through building information modeling, integration and sustainability of a building can be improved in the following ways:

1. *Design optimization and constructability*
   Through BIM, a three-dimensional model of the building can be produced, helping designers understand how their designs will be implemented during the construction phase. During the design phase, designers are able to fully consider a range of construction technologies, construction processes, and construction procedures for optimization. In doing so, they can simplify construction processes, make designs more practical, feasible, and achieve greater integration within the construction plan; thereby reducing uncertainty and ensure design integrity, achievable at the construction phase. BIM is therefore conducive to design optimization and constructability. Figure 16.4 shows a model of duct work and piping for a section of the building. From the model, potential construction problems can be identified and resolved.

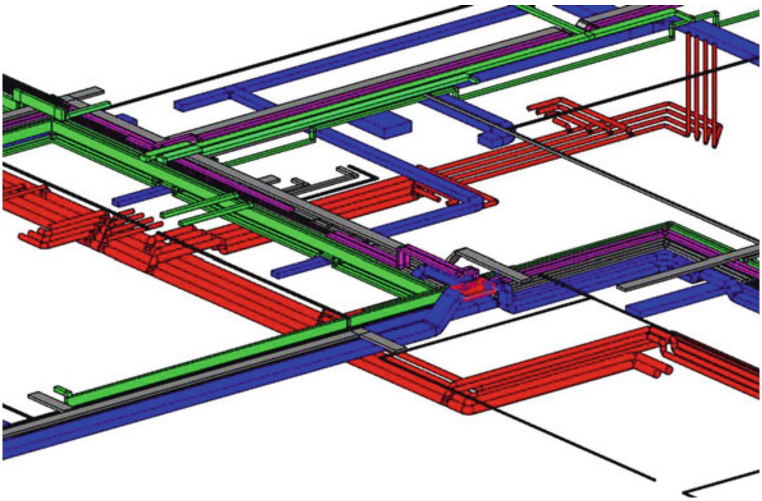

**Fig. 16.4** Design optimization base on BIM

2. *Direct application of design data in the construction phase*
   BIM provides a 'collaboration platform' for both design and construction. Both design and construction data and the results of production must meet the data mode and transmission standards of the model, therefore, information that arises in the design phase are useful in the construction phase (e.g., design drawings, tables, parameters). Using BIM, these data can be easily found and directly applied immediately. In contrast, traditional management models function with construction teams who struggle to access information and once found, make it accessible to others (Fig. 16.5).
3. *Enhance understanding of a building's design*
   Detailed communication and full integration of design and construction information generated by BIM can help construction managers to understand the intentions of designers, the performance of equipment together with technical parameters, and design key principles. This enables construction staff both to realize the design more completely and help ensure that the client's requirements are met. BIM models can also be used to help construction workers plan their schedules which encourage safe, productive working patterns.
4. *Provide additional professional and comprehensive consulting services*
   BIM allows in-depth communication and full integration between design and construction professionals which can help investors visualize details relating to form, structure, space, and finishings in the early phases of the project. As a result, this gives the opportunity for architects and engineers to provide clients and investors with more comprehensive and more professional consulting services. Figure 16.6 shows the range of visual information that can be produced from a single model.
5. *Contribute to construction cost control*
   The integration of design and construction and the improved management of

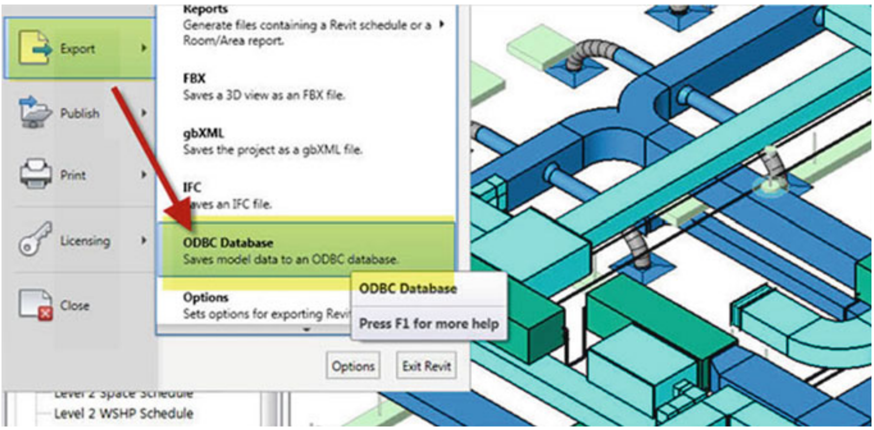


**Fig. 16.5** Construction data export from design software

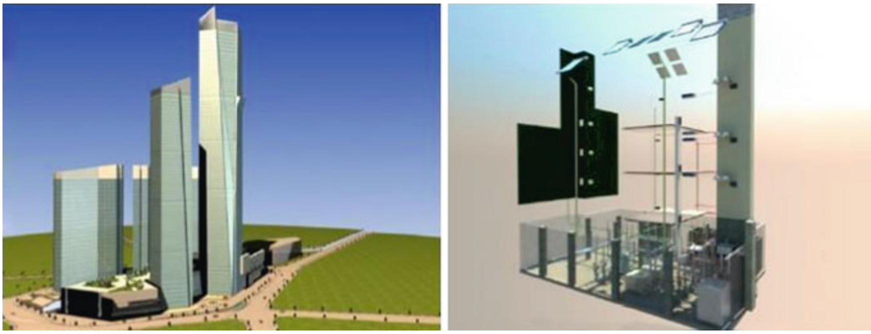

**Fig. 16.6** Virtual reality in sustainable building projects

this link provided by BIM can improve the concerns relating to the investment required thereby helping to avoid a mismatch between design and cost control. By optimizing the design, reducing the error rate of drawings, minimizing problems in the quality of production and increasing the transparency, and controllability of the project, we can reduce cost of buildings. Through close cooperation between design and construction professionals and minimizing late design changes and engineering rework caused by miscommunication, we can also save costs. Ultimately we can achieve project cost control and project sustainability.

6. *Facilitate environmental and energy consumption analysis*
   If the Building Information Model is developed based on uniform data standards it should be possible for data transfer to other software applications with a unified data 'interface'. This enables other applications to benefit directly from the BIM. Early in the design phase, with the application of BIM technology, the architect may create a three-dimensional virtual model of the building which contains a large volume of design information, including geometry, material properties, component properties, and so on. These raw data can be directly applied without any additional processing to provide the basis for environmental and energy analysis using software tools (Fig. 16.7).

Thus, time spent manually inputting data (e.g., geometry, structure, site, climate, HVAC data) by environmental or energy analysts is reduced as data can be extracted directly from the corresponding building information model, and imported directly into the relevant environmental and energy analysis software.

For example, when using BIM with the *Green Building Studio*® software for energy simulation (Autodesk 2011), architects simply enter the building type and geographic location by hand and the software will automatically extract the useful information from the building information model to establish an accurate thermal model (including reasonable partition and azimuth), and make intelligent assumptions for different types of building space according to local building regulations. The building performance may be modeled hourly with typical local weather data. The building's annual energy consumption, costs, heating and

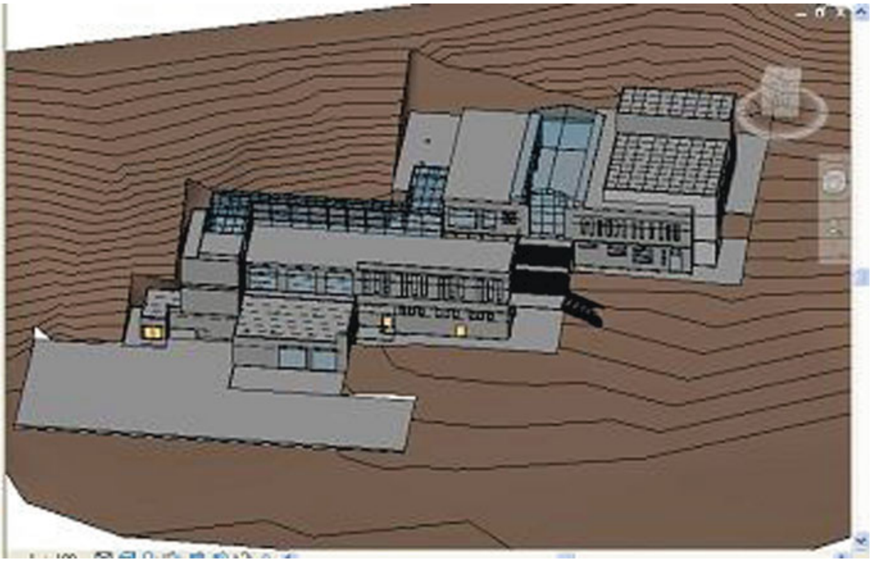

**Fig. 16.7** Environmental analysis in sustainable building projects

cooling loads, and other data are included in the analysis results. Using such software with comprehensive databases reduces the complexity of simulation, thereby allowing accurate parameters to be used which produces robust results with relative ease.

Simplifying the analysis process helps architects integrate a variety of data and simulation results into preconstruction planning and program design, fairly easily and quickly. For example, architects can accurately integrate many different forms of space, materials, systems, and adapt them to the physiological and psychological needs of different user groups. A BIM model designed to assess indoor environmental quality can accurately simulate interaction between internal and external surfaces to facilitate an accurate appraisal. Architects can use simulation results to optimize design and performance, according to sustainable architectural and physical principles.

In addition, architects using BIM can accurately measure the ecological impact of buildings on the land and integrate more ecological factors such as sympathetic landscapes, sustainable drainage, and water features into building forms. Restoration of ecosystems and encouraging water conservation can also be achieved.

Finally, BIM provides a standard platform for information integration and sharing, and an object-oriented architectural design method. In addition to providing various property information of building and a sustainable building design process (thermal, visual, sound, etc.), the architect can also model the chemical composition of materials, obtain energy consumption information, and gage the proportion of recycled components by BIM. Architects can also examine the use of sustainable building materials and components to enhance environmental performance.

## 16.5 Conclusions

The *Sustainable Building* project requires sophisticated information systems to manage the information requirements at all stages of the design, construction, operation, and demolition of the building. Two recommended elements for efficient, effective information management are the application of systems to manage information requirements and the adoption of sophisticated BIM software to meet the needs of all the parties involved. Using BIM it is possible to model and simulate all aspects of a building's production and performance and to ensure that the needs of the client and community for a sustainable built environment are met. BIM enables: the collaborative design of buildings; the integration of building design and construction; design optimization and constructability; the direct application of design data in the construction phase; the enhanced understanding of construction workers; additional professional and construction services; improved cost control; and the ability to undertake improved environmental and energy consumption analysis. The future of construction will look towards BIM and developments in the area of information management to facilitate the successful delivery of sustainable buildings in years to come.

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# Chapter 17
# Sustainable Construction Materials

**Andrew Miller and Kenneth Ip**

**Abstract** This chapter identifies the means by which construction materials can be evaluated with respect to their sustainability. It identifies the key issues that impact on the sustainability of construction materials and the methodologies commonly used to assess them. Examples of sustainable materials are used to identify their potential use in construction. *Learning outcomes*: on successful completion of this chapter, readers will be able to: (1) appreciate the role and impact of building materials within a building's life cycle; (2) comprehend the concepts of embodied energy, gross energy requirement (GER), and process energy requirement (PER); (3) have knowledge of renewable materials and how they are grown, processed, and used as building components; and (4) have an appreciation of sustainable construction materials in the context of green building assessment methods.

**Keywords** Construction materials · Life-cycle assessment · Renewable resources · Environmental impact · BREEAM

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## 17.1 Introduction

There are hundreds of different materials that are used in the construction of any new building. Their functions, and therefore their physical properties, can be very different. It is useful, when making comparisons, to consider materials with a similar function. Materials used for the structure of buildings require properties of strength, whereas other parts, such as the envelope, are selected for their insulation or esthetic properties. Comparisons become more complex when materials perform more than one function such as load-bearing walls that provide good thermal insulation.

There is also a need to distinguish between finite resources and renewable resources when reviewing the sustainability of a material. Some materials, despite being nonrenewable may be considered plentiful on earth; however, the consequences and impacts of mining them may be considered unacceptable. The effect of construction material selection will impact upon sustainability throughout the lifetime of both the material and that of the building itself. The need to maintain the building, replacing individual components, disposing of the old, and procuring the new will have environmental impact from cradle to grave.

## 17.2 Materials and Sustainability

Construction materials currently constitute between 40 and 50 % of the total materials used worldwide on an annual basis (CIB 2008). In the UK, 420 million tonnes of materials are used in construction each year, equivalent to 7 tonnes per inhabitant (Lazarus 2004). It is therefore essential that we optimize their use, minimizing the impact on the planet and increasing overall sustainability.

Optimization of use can include reducing wastage and ensuring that materials that have not reached the end of their useful life when the building has reached the end of its useful life are reused or recycled whenever possible. Some materials are difficult to separate at the time of building demolition and design of new buildings must therefore consider the deconstruction and separation of buildings to their constituent components and materials. For example, the use of cement mortars made it difficult and labor intensive to clean and reuse bricks, whereas the use of lime mortars facilitates the process. Metals, however, have commonly been separated and recycled at demolition stage primarily because of their financial value and the economic viability of doing so. Materials that are reused or recycled have the double advantage of reducing landfill as well as displacing the need for virgin materials.

Wastage of materials at the construction stage also constitutes poor sustainability and excellent guidance on good practice is available through documents from organizations such as WRAP, the UK organization with a mission of waste prevention and the construction industry research and information association (CIRIA). Modern Methods of Construction, including off-site construction have also made an impact on sustainability through mass production and improvement in working conditions reducing wastage from offcuts and aborted work.

The impact of material consumption is experienced in many ways, through depletion of natural resources, waste during construction, and disposal at the end of their useful life. They have further impacts through the energy and water consumed and pollutants emitted throughout their processing and transportation. Careful selection of materials can therefore make a significant difference to the overall environmental impact of a building.

Traditional building construction utilized local materials that were readily available which led to styles of vernacular architecture including timber and stone. Modern methods of transportation-facilitated materials being sourced from around the world and modern manufacturing processes enabled the development of construction materials which were lighter, more manageable, and easier to use than their traditional counterparts. As material science and technologies have progressed, more composite materials and products have come onto the market.

The advantages of modern materials are evident in that they may save time and money, require less skilled labor to construct, and less maintenance during the useful life of the building. On the other hand, the environmental impacts of processing and transporting these materials and the socio/economic impacts of losing a skilled workforce are less evident. Neither is the impact of consuming finite resources.

Professionals in the construction industry are responsible for the appropriate use of materials and to enable their sustainability. This requires understanding of the impacts relating to materials throughout their life cycle, from their raw components, through to their eventual disposal at the end of the useful life of the building. It also entails the ability to balance the consequences from a variety of very different impacts in order to make appropriate judgements.

Collation of data in order to make sustainability judgments is notoriously difficult and available data are often incompatible, having been established using different methodologies. Nevertheless, there are now some national databases and internationally agreed protocols that can be used to facilitate comparison of materials.

Common lifecycle analysis (LCA) procedures have been established and publications such as *Environmental Profiles* (Howard et al. 1999) have established detailed methodologies for the determination of environmental impacts of individual materials. These in turn are included in different environmental assessment models that enable the impacts of building materials to be evaluated within the broader context of the lifetime impact of a building.

## 17.3 World Resources

The current rate of extraction of natural resources from the planet is around 60 billion tonnes per annum and has risen dramatically in recent years (Materialflows 2011). It has risen from 40 to 60 billion tonnes per year and at the same time the world population has risen from 4.4 to 6.4 billion inhabitants.

These materials are made up of both renewable and nonrenewable resources. Renewable resources such as timber and the products of agriculture including plants, food, and animal stock must be properly managed in order to maintain their sustainability. Nonrenewable resources including fossil fuels, metals, and minerals are by definition finite and must be consumed in a sustainable way, optimizing their efficiency through carefully considered selection, minimizing waste, recycling, and reusing wherever possible.

### 17.3.1 Non-renewable Materials

The construction and operation of buildings place heavy demands on nonrenewable resources including fossil fuels, metals, and minerals. There are some bleak predictions concerning consumption rates of fossil fuels and possible dates when supplies will be exhausted. The incentive to conserve these resources is heightened by the realization that burning such fuels is a significant cause of carbon dioxide emissions resulting in climate change.

Some construction materials are considered plentiful within the composition of the earth; consequently less attention is directed toward managing these resources in a sustainable manner. For example, iron ore is the key ingredient of steel which constitutes a high proportion of metal used in the construction industry. World production was 2.2 billion tonnes in 2009, with world resources estimated to exceed 230 billion tonnes. In resource terms it is considered plentiful; however, there is little demand for construction in the regions where the ore is mined with resulting high cost of transportation in both financial and energy terms.

The geographical location of raw materials is also a significant factor in considering the environmental burdens of their consumption. It is the more affluent regions of the world that demand resources which are being mined further afield. Growing demand is also resulting in the increased difficulty and expense of mining as easily accessible resources are depleted and more complex mining is required.

The increased difficulty in mining certain materials leads to increased '*overburden*'. This is the amount of other material including rock and topsoil removed in order to access the required material. The overburden currently stands at around 60 %, resulting in the removal of a further 40 billion tonnes of matter to provide the total of 60 billion tonnes of materials being consumed (FOE 2009). The impact on the natural environment is considerable. Furthermore, the impact on the landscape and ecology can be devastating; however, it is the economics of production and supply that is limiting the rate at which some materials are being depleted.

### *17.3.2 Renewable Materials*

The use of renewable materials is traditional to the construction industry. Timber is used extensively in both the structure and fittings for buildings but requires long-term resource management as the growth of trees for structural timber can be 100 years or more. However, shorter rotation plants and crops such as straw or hemp can be readily used for the construction of buildings and can be harvested on an annual basis.

An additional advantage of natural renewable materials like trees and plants is that they lock in atmospheric carbon dioxide during their growth period while emitting oxygen back into the atmosphere. They are often considered as being carbon neutral or even carbon negative when evaluating their carbon footprint and environmental impact on the planet.

The transportation implication for shorter rotation materials can be far less compared with finite resources, as they are often grown in the same region where the construction site is located. Benefits are experienced in reduced demand for fossil fuels resulting in emissions and the economic cost of transportation.

## 17.4 Life Cycle of Building Materials

It is important to consider building materials not just for their function within a completed building, but for their impact on the planet and the environment both before and after their functional lifetime within the building. Materials impact on finite resource depletion as well as pollution and landfill implications at the end of their useful life.

The life cycle of building materials commences with the ‘winning’ (e.g., mining) of raw materials and includes all stages in the production of construction products and components, construction of the building, maintenance, reuse or recycling, and eventual disposal at the end of its useful life. In addition, the environmental impacts also include the effects of all these processes as well as those of transportation within and between the stages in the life cycle as depicted in Fig. 17.1.

Renewable materials such as timber, together with shorter term crops such as hemp and straw, can be assessed to include the impacts from planting and growing, prior to harvesting, before the material enters the construction process. In this way, it is possible to achieve positive environmental impacts due to the sequestration of atmospheric carbon dioxide during the growth of the plants and trees.

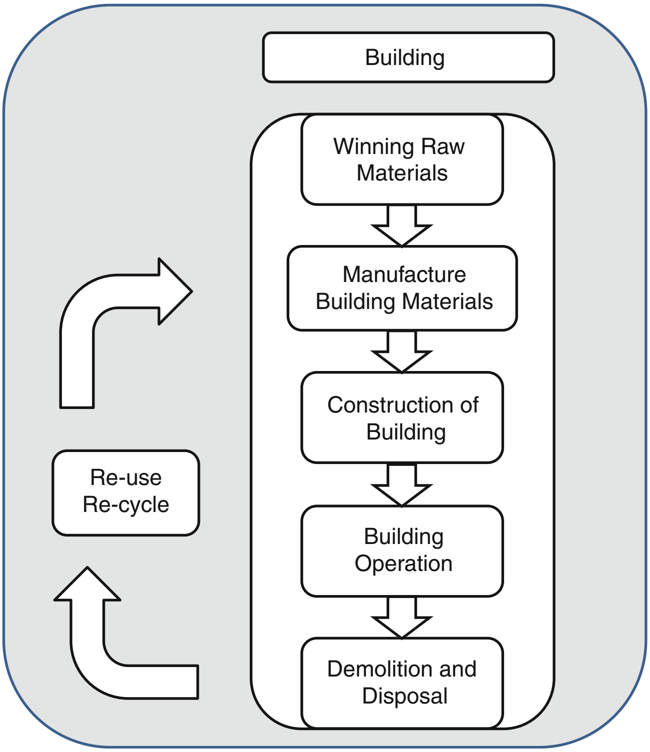


**Fig. 17.1** Life cycle of building materials

## 17.5 Life-Cycle Assessment

The use of a lifecycle assessment (LCA) methodology can facilitate comparisons among materials. It can be used to evaluate different environmental impacts and burdens within the longer life cycle of the buildings themselves. However, many assumptions are made in establishing LCA results and comparisons among results in different databases can be misleading without a clear definition of the assumptions adopted.

Life-cycle assessment methodology is generic and is described as having four phases:

- Goal and scope definition;
- Inventory analysis;
- Impact assessment;
- Interpretation.

International standard procedures are defined in *Environmental Management Life-Cycle Assessment—principles and framework* (ISO 14040 2006).

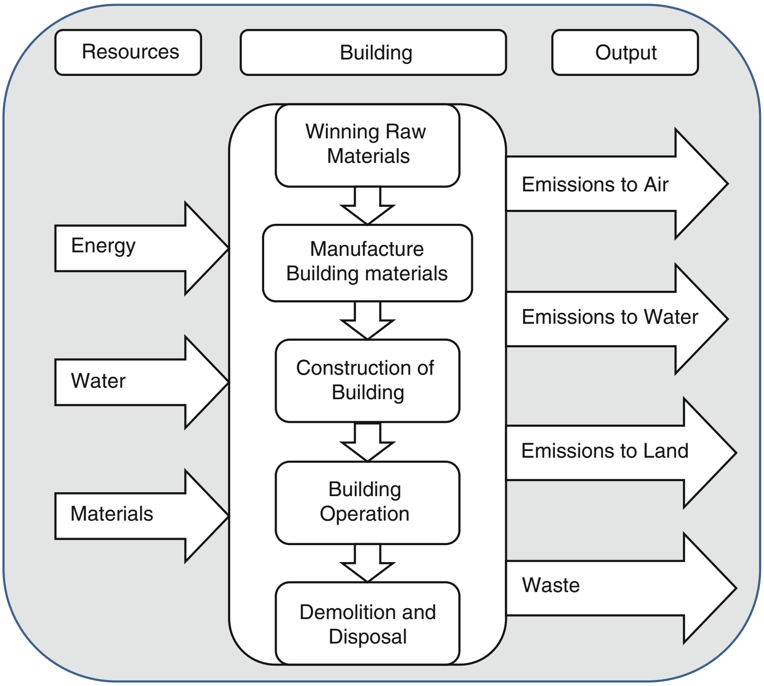


**Fig. 17.2** Life cycle of environmental impacts of buildings

Assessment of the environmental impacts of buildings and their component materials include the resources they consume and the emissions they make throughout their life cycle as illustrated in Fig. 17.2.

## *17.5.1 Key Terms and Issues*

### 17.5.1.1 Functional Unit

The functional unit is the basis on which the performance of a material or combination of materials can be quantified. It can be made on the basis of mass, volume, or area, or based on the overall product. Thus, when evaluating bricks or blocks they may be considered in unit terms of 'per kilogram of brick' or 'per cubic meter of brick'. However, neither of these units provides direct indication of the impact within a building, but a functional unit of 'one square meter of wall' may have better relevance. This enables the design of the wall to be taken into account as it could be constructed from single or multiple bricks in thickness.

The definition of the functional unit is important to the comparison of building components. Different materials for wall construction could be compared on the basis of the area of wall produced, but would need to enable consideration of their ability to provide a weatherproof envelope as well as structural and thermal performance.

#### 17.5.1.2 Boundaries

The definition of system boundaries clarifies what is included or excluded from the analysis. For example, transportation is commonly included within LCA, but additional clarity is required to define whether calculations assume a one-way delivery journey or a two-way journey (with an empty return vehicle); and whether it considers only the fuel consumed or allows for the manufacture and maintenance of the vehicle and transportation network.

#### 17.5.1.3 Useful Life

The useful life of the material defines the duration of the life cycle, identifying a need for replacement and consequently a second set of environmental impacts. It may be particularly important when selecting materials for a building, which itself will have a useful life far longer than the individual component.

A softwood window frame might need replacing after 15 years, whereas hardwood could last 25 years. Alternatively, a PVCu (plastic) frame could last even longer, say 30 years, and require less maintenance. This then needs to be considered in the context of the useful life of the building and the number of window frame replacements in a lifetime of 60 or 100 years. The resources can be evaluated in terms of energy and water embodied within the building materials and components, and impacts from emissions can be assessed through climate change, ecological damage, and effects on health both for humans as well as animals and fish. Comparison of individual materials based on the aggregation of all of the environmental impacts is a complex problem requiring an agreed methodology for assessing individual components and an agreed weighting system for summing the impacts.

The Environmental Profiles system established by the building research establishment (BRE) in the UK is commonly accepted as the basis for material choice and is used within environmental assessment methods to evaluate whole buildings, such as the code for sustainable homes (CSH) and the building research establishment environmental assessment method (BREEAM).

### *17.5.2 Embodied Energy*

The embodied energy of a material refers to the amount of energy consumed in providing that material. There are, however, many definitions of the term *embodied energy* and in order to make fair and useful comparison among different materials, it is necessary to understand clearly which definition is being used.

A common definition of embodied energy is: *'the energy consumed up to the end of the manufacturing process'*—also referred to as *'cradle to gate'*. Other definitions include material transportation to the construction site (cradle to site), or even in the construction processes, finishing with the completed building. The latter two definitions are clearly site specific and relate only to an individual building.

The definition of embodied energy is further complicated when considering the scope of the analysis, which can include the gross energy requirement (GER) or more simply the process energy requirement (PER). The inclusion of energy for transportation of materials between processes is a further element requiring clarification before figures can be compared.

#### 17.5.2.1 Gross Energy Requirement

The gross energy requirement is a measure of the total energy inputs to a specific material. It can be considered as the total energy consumption for which the finished material is responsible. Thus, it not only includes the total energy consumed in winning the raw materials, transporting, and manufacturing of building materials and components themselves, but also the manufacture and maintenance of all plant and machinery used in winning and processing those materials, the transportation of the labor force for all associated activities, and the repair of the damage caused during these processes.

#### 17.5.2.2 Process Energy Requirement

Process energy requirement is the total energy consumed in the processes directly undergone by the building material or product. It will include the energy consumed by the plant and machinery throughout the processing, but not that of the second and higher generation consumptions of the machinery that made the machinery and the repair of the damage caused by the processes.

Different approaches can be adopted when evaluating PER and care is required when using published data in order to make comparisons. Common issues where clarity of assumptions and methodology is required are:

- Apportioning energy where more than one product undergoes the same process or one is a by-product of another;
- Inclusion of transportation and how return journeys of the delivery vehicle is considered;
- Apportioning transportation energy for a part load on a ship or other mode of transportation.

The building services research and information association (BSRIA) published a comprehensive document identifying assumptions made in published figures (Hammond and Jones 2011). It is based on research undertaken at Bath University in the UK and incorporates their inventory of carbon and energy (ICE).

#### 17.5.2.3 Embodied Carbon

Interest in embodied energy is significant not only because of the impact on the depletion of fossil fuels, but also the emissions of pollutants during the consumption of these fuels. The latter is referred to as embodied carbon.

Although embodied energy and embodied carbon are directly related, the impact of any material on resource depletion and on greenhouse gas emissions can be very different. This depends on the type of primary fuel consumed and how the electricity was generated. Consumption of renewable energy may be considered to have zero emissions provided the embodied energy of the collectors and generators are neglected. Similarly, nuclear energy will also have zero carbon emissions. The embodied carbon is therefore dependent upon the fuel mix in the location where the processing takes place.

Some materials are even classed as having negative embodied carbon. This occurs when calculations include the carbon sequestered during their growth. Trees and short-term crops used for building materials sequester atmospheric carbon dioxide during their growing period, the weight of which may be greater than the emissions during manufacture.

## 17.6 Life-Cycle Assessment of Building Materials

Construction materials are selected primarily for their physical properties, used for structure, weather proofing, insulating, and also for their esthetic quality. Choice is also affected by value for money, including initial costs and durability. Appropriate materials must also be compared in terms of their environmental impact which may be significant and have effect outside the performance of the building itself.

Evaluation of physical properties and value for money is relatively straightforward with clear definition of units and methods of measurement. Environmental impact, however, is more complex, involving different types of impacts including emissions of different gases and pollutants to the atmosphere; consumption of other resources such as energy and water throughout their life cycle; depletion of natural resources; and finally implications for disposal at the end of their useful life. Impact types are calculated in different ways and there is no simple method of weighting these impacts within a single index to facilitate material choice. The problem is exacerbated as individual impact types will have different priorities depending on what region of the world the assessment is conducted in.

Over the years, standard procedures have been developed to help ensure that evaluation figures are comparable, with common boundary conditions and procedures of measurement. Assessment methods such as the Environmental Profiles developed by the BRE in the UK (Howard et al. 1999) have enabled materials to be compared on a common basis considering boundaries of cradle to gate, cradle to site, and cradle to grave assuming a 60-year useful life.

**Table 17.1** Environmental impact categories, issues measured, and weightings for environmental profiles (*Source* Anderson et al. 2009)

| Environmental impact category | Environmental issue measured | Weighting (%) |
|---|---|---|
| Climate change | Global warming or greenhouse gas emission | 21.6 |
| Water extraction | Mains, surface, and groundwater consumption | 11.7 |
| Mineral resource extraction | Metal ore, mineral, and aggregate consumption | 9.8 |
| Stratospheric ozone depletion | Emission of gases that destroy the ozone layer | 9.1 |
| Human toxicity | Pollutants that are toxic to humans | 8.6 |
| Ecotoxicity to freshwater | Pollutants that are toxic to freshwater ecosystems | 8.6 |
| Nuclear waste (higher level) | High and intermediate level radioactive waste from nuclear energy industry | 8.2 |
| Ecotoxicity to land | Pollutants that are toxic to terrestrial ecosystems | 8.0 |
| Waste disposal | Material sent to landfill or incineration | 7.7 |
| Fossil fuel depletion | Depletion of oil, coal, or gas reserves | 3.3 |
| Eutrophication | Water pollutants that promote algal blooms | 3.0 |
| Photochemical ozone creation | Air pollutants that react with sunlight and $NO_x$ to produce low level ozone | 0.2 |
| Acidification | Emissions that cause acid rain | <0.1 |

### *17.6.1 Environmental Profiles*

The environmental profiles of materials established by the BRE include 13 environmental issues which are weighted in accordance with those shown in Table 17.1.

These profiles are key for the analysis of materials in the UK as they are used as reference to gain credits for materials selection in BREEAM and CSH assessments.

## 17.7 BRE Environmental Assessment Method

There are many systems in place throughout the world to determine the environmental impact of buildings and assist building industry professionals in selecting appropriate materials and design solutions in reducing environmental impacts. One of the first systems was BREEAM for offices, published in the UK in 1993.

The assessment of new domestic housing has evolved into the CSH which has rapidly established itself as a reference for good environmental design (DCLG 2008). The system involves a star rating from one to six stars, more stars indicating greater environmental performance. Many housing associations which provide social housing require minimum standards of three or four star homes which demonstrate their commitment to improving environmental issues.

The CSH, similar to other BREEAM systems, is evaluated under nine categories namely Energy and Carbon Dioxide Emissions, Water, Materials, Surface Water Runoff, Waste, Pollution, Health and Well-being, Management, and Ecology.

The choice of materials is clearly recognized within the Materials category, but will have impact within the categories of Waste and Pollution. The Materials category includes three assessments, M1 for the processes involved in producing the building materials and M2 and M3 for the responsible sourcing of the raw materials both for the basic building construction and the finishes.

### *17.7.1 M1: Environmental Impact of Materials*

Building materials are assessed against the *Green Guide to Specification* (Anderson et al. 2009) which itself has been based on analysis undertaken for the environmental profiles (Howard et al. 1999). The Green Guide to Specification employs all 13 categories used in the Environmental Profiles and produces a weighted performance with ratings of A+ to E, with A+ representing the best environmental performance and the lowest environmental burden.

Comparison of materials is facilitated as the Green Guide is organized by building elements including external walls, internal walls, roofs, floors, and windows. The guide rates a material against all 13 categories together with a summary rating overall. An example of the data presented is shown in Table 17.2.

It is mandatory within the Code for Sustainable Homes scoring system to achieve ratings between A+ and D for at least three of the five key elements—roof, external walls, internal walls, upper and ground floors, and windows. If this mandatory requirement is met higher credit is given to the better rated materials.

### *17.7.2 M2 and M3: Responsible Sourcing of Materials—Basic Elements and Finishes*

Materials achieving credits within these categories are required to be certified by appropriate third-party assessments. They would normally include certification of legal sourcing of timber materials, chain of custody from source for new materials, or for the virgin component of composite recycled materials.

## 17.8 Renewable Building Materials

Renewable materials originate from plants and trees which can be harvested and regrown within a few human generations. They include short-term crops that grow within a seasonal life cycle as well as timber from managed forests and woodlands that may take a few hundred years to replace.

**Table 17.2** Example of ratings from green guide to specification (*Source* Anderson et al. 2009)

| Brick and timber-framed construction<br>All building types | Element number | Summary Rating | Climate change | Water extraction | Mineral resource extraction | Stratospheric ozone depletion | Human toxicity | Ecotoxicity to freshwater | Nuclear waste (higher level) | Ecotoxicity to land | Waste disposal | Fossil fuel depletion | Eutrophication | Photochemical ozone creation | Acidification | Typical replacement interval | Embodied $CO_2$ (kg $CO_2$ eq.) | Recycled content (kg) | Recycled content (%) | Recycled currently at EOL (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Brickwork, cement mortar:** | | | | | | | | | | | | | | | | | | | | |
| cement-bonded particle board, timber frame with insulation, vapour control layer, plasterboard on battens, paint | 806190536 | A+ | A | A+ | A+ | A | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A | 60+ | 82 | 5.7 | 3 | 73 |
| OSB/3 sheathing, timber frame with insulation, vapour control layer, plasterboard on battens, paint | 806190047 | A+ | A+ | A+ | A+ | A | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A | 60+ | 52 | 8.8 | 5 | 76 |
| plywood (temperate EN 636-2) sheathing, timber frame with insulation, vapour control layer, plasterboard on battens, paint | 806190056 | A+ | A+ | A+ | A+ | B | A+ | A+ | A | A | A+ | A | A+ | A | A | 60+ | 55 | 4.1 | 2 | 75 |
| **Reclaimed brickwork:** | | | | | | | | | | | | | | | | | | | | |
| cement mortar, OSB/3 sheathing, insulation, timber frame, vapour control layer, plasterboard on battens, paint | 806190543 | A+ | A+ | A+ | A+ | A | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A+ | A+ | 60+ | 28 | 134 | 74 | 79 |
| plywood (temperate EN 636-2) sheathing, timber frame with insulation, vapour control layer, plasterboard on battens, paint | 806190051 | A+ | A+ | A+ | A+ | A | A+ | A+ | A+ | A | A+ | A+ | A+ | A+ | A+ | 60+ | 31 | 129 | 69 | 78 |

## *17.8.1 Short-Term Crops*

The CIRIA publish a handbook for crops in construction (Cripps et al. 2004) which reviews the socioeconomic benefits as well as the environmental impacts of natural construction materials. It features structural and insulation materials as well as finishes and floor coverings, identifying their physical properties as well as their ecological advantages and disadvantages.

Materials such as thatch and straw have been used in buildings for centuries. Despite this, they have generally been replaced by modern alternatives which are quicker and often require less skill to work with. Understanding the physical properties of these organic materials has led to increased interest in using them for construction, often using local sources and components of the crop that would otherwise be discarded.

Straw bale and hemp are used here to illustrate the use of short-term crops in modern construction. Straw is a by-product of cereal crops which, even during the twentieth century, was burned in fields after harvest. Hemp is used in construction because of its strong fibers, however, it also demonstrates a variety of pharmaceutical properties.

#### 17.8.1.1 Straw Bale

Traditional straw bale has been used for the construction of domestic buildings for centuries and was facilitated by the invention of the mechanical baler which formed tighter bales of a uniform size. Straw bales appropriately stacked together can form highly insulated walls. Once the surfaces are rendered they become durable and weatherproof although attention is necessary for roof detail, where wide overhangs are required to prevent water penetration. Straw bale can be used as a structural element, generally for single-story dwellings but is more flexible as infill within a timber frame. It is difficult to define the thermal performance of straw bale construction because of the variability in the straw itself and the density of packing. However, Danish studies have estimated a design value of 0.18 $W/m^2$ K would be reasonable for a standard straw bale (Munch-Andersen and Andersen 2011).

#### 17.8.1.2 Hemp

Industrial hemp is a very fast growing plant of the *Cannabis Sativa* family that has a low narcotic component. Its fibers are very strong and the longer ones are used in concrete to improve both compressive and tensile strength; it also reduces shrinking and cracking. Mixed with lime it can be used to form an infill material for a timber frame, forming a rigid material with good insulating properties that is lightweight and breathable.

Hemp is one of the fastest growing crops in the world, second to bamboo. It requires very little attention or fertilization during its growth and is a useful rotation crop. The process of photosynthesis required for plant growth captures carbon dioxide from the atmosphere, and therefore in some circumstances, leads to hemp lime construction being considered as having a negative carbon footprint. More carbon is captured during the growth period than is emitted due to energy consumption in manufacture and transport.

World leaders in the development of hemp use in modern sustainable construction include Rachael Bevan and Tom Woolley, whose book includes case study examples together with accounts of life-cycle analysis (Bevan and Woolley 2008).

### *17.8.2 Timber*

The use of wood as a construction material can be considered as a highly sustainable option. It is a natural material which, if properly managed, is renewable and will sequester carbon throughout its period of growth. In addition, at the end of its useful life as a building material, it may be reused or recycled, may be burnt as a fuel, or will decompose naturally in landfill.

There are records of timber construction in ancient Chinese culture with evidence of *dougong* (cap and block) structural elements being used in the eighth century BC. Timber frame has been a feature of building construction in the UK for many centuries with the pattern of the timber structural framework being clearly visible in many historic towns and villages. The roof structures of the magnificent medieval cathedrals also illustrate the essential nature of timber in construction throughout history.

The growth of trees is dependent upon the sequestration of carbon through the process of photosynthesis. Trees extract carbon dioxide from the atmosphere and release oxygen, creating biomass and reducing carbon dioxide concentration in the atmosphere. The carbon is 'locked' within a structure of a tree throughout its growth and for the duration of its use within the timber products made from that tree. It is only released when the timber is eventually disposed of either through decomposing naturally or through combustion. The latter may be utilized as a fuel source.

The use of timber in construction has a long-term advantage to the environment, provided that the forests and woodlands are appropriately managed and new trees are planted to replace those that are felled. It is estimated that the average tree absorbs approximately 55 kg of $CO_2$ and gives off 40 kg of oxygen when growing 2 kg of wood (TTF 1998). During its growth period, a tree therefore has a positive impact on the environment through the reduction in greenhouse gases. Environmental assessments in the UK such as BREEAM and the CSH require appropriate certification such as those issued by the forest stewardship council (FSC) for timber used either for structural or finishes.

Through appropriate forest management and production, efficient use can be made of the material discarded from the felled trees for composite timber products and garden mulches. The supply of timber for the construction industry can be fully sustainable when harvested timber is replaced through replanting.

In the UK, a high proportion of construction timber is imported, yet some regions including Sussex in the southeast of England are heavily wooded. It is often quoted that the climate in England is not suited for the successful growth of construction timber as trees grow too quickly, failing to achieve the required structural properties. While rapid growth means faster absorption of $CO_2$, the resulting timber cannot be used directly for construction.

Traditionally, the building design, including dimensions and span widths, depended upon the size and quality of timber available and the skill of the craftsmen who constructed the buildings. Woodland management undertaken to serve the construction industry also had to compete with the demand for timber for ship construction.

Modern timber construction, however, utilizes engineered timber products as well as smaller tree sections which enable efficient use of the timber and greater flexibility with sizes. Factory manufacture of frames and panels can also improve quality and reduce wastage, again improving the resource efficiency of timber.

However, processed timber products such as glulam (glue laminated timber) provide excellent alternatives to natural timber sections and although they require energy for manufacture, they usually incorporate less embodied energy than alternative structural materials.

#### 17.8.2.1 Timber Life Cycle

The life cycle of timber from sustainable sources can be traced through every stage from cradle to factory gate, and beyond to construction, maintenance, and to disposal when appropriate. However, the cradle to factory gate analysis is most common. It includes:

- Seed gathering and propagation;
- Seedling planting and forest management including fertilizing, protection from animals, and thinning;
- Harvesting the mature trees including forestry activities;
- Drying and seasoning felled timber;
- Processing slab wood and rough sawn timber;
- Secondary processing timber joinery;
- Transport within and between each of these stages.

Trees used for structural timber mature over many decades. Softwood forests may be harvested after 50 years but hardwood trees may take over 100 years to mature.

One important strategy for sustainable woodland management is coppicing, thinning the canopy to allow sunlight to the woodland floor on a cyclic basis which facilitates biodiversity at ground level. The vigorous growth generated in the coppiced trees also represents an accelerated rate of carbon sequestration reducing the build-up of carbon dioxide in the atmosphere.

Engineered timber products also utilize woodland coppiced materials where hardwood such as sweet chestnut is harvested through coppicing. Trees are cut down to ground level in relatively short cycles which promote vigorous growth and produce poles up to 200 mm in diameter. Traditionally, coppiced material was used for fence poles, tool handles, and a wide range of applications. Modern gluing and jointing techniques have enabled short lengths of timber with small cross-sectional areas to be jointed and laminated to produce large structural members for construction.

#### 17.8.2.2 Engineered Timber Products

There are many environmental advantages of using timber in contemporary building construction, utilizing a material that enhances the quality of life for everyone during its growth period, and which will ultimately biodegrade to its component parts. One additional advantage of using engineered timber products is that high quality structural elements can be produced from timber that would otherwise not have been suitable for construction. It reduces waste and adds value to material for which there was little demand, and therefore encourages more active woodland management.

There is a wide variety of engineered timber products that are used in furniture, finishes, and other decorative features that are not designed for structural use. There is also some environmental concern about some of the adhesives that have been used and the potential for off-gassing. Two products, however, that are enhancing the use of timber in modern construction are *glue laminated timber* (*glulam*) and *structurally insulated panels* (SIPS).

#### 17.8.2.3 Glue Laminated Timber

Glulam is a manufactured composite material made by finger jointing different lengths of coppiced material that has been cut to a uniform cross-section, and then further gluing individual lengths to form structural members of any desired cross-section and length. These can be bent during manufacture to form wide spanning curved beams which have a beautiful esthetic.

Techniques have been developed to utilize green coppice, thus not only reducing wastage by using short sections of material, but reducing energy which would normally be required for the drying process.

#### 17.8.2.4 Structurally Insulated Panels

The structurally insulated panel has been created to facilitate fast, on-site construction using precision manufactured products that have been constructed in a factory and provide both load bearing and thermal insulation properties. Various sheet materials are used to sandwich insulating materials such as expanded or extruded polystyrene, or any other insulating material, including straw bales to form a composite panel. The panel is manufactured to include appropriate vapor barriers and may also include service distribution ducts.

Panels can be manufactured to many size specifications; however, there are implications with respect to handling and transportation. A typical 2.4 × 2.4 m panel can provide a complete floor height and sufficient flexibility for the design of the floor plan. The reduced number of joints improves airtightness, another advantage in the construction of low energy buildings.

## 17.9 Conclusions

Construction materials are required to provide many different functions for the structure, envelope, services, and esthetic of any buildings. These materials are sourced throughout the world and their mining and harvesting, transportation, and manufacture will have varying impacts on the natural environment. Consideration of their sustainability relates to all of these impacts together with social and economic factors and the finite nature of the resource. Implementation of various calculation methodologies such as LCA can highlight the extent to which energy is consumed in providing certain goods. Further, the use of renewable materials and the approach we adopt in constructing buildings will play a vital role in mitigating future carbon emissions. Selection of sustainable construction materials must therefore be based on a clear understanding of the key issues, and reduce the negative impact on people and the natural environment while promoting social wellbeing and achieving economic viability.

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# Chapter 18
# Assessing the Built Environment

**Martin Townsend**

**Abstract** This chapter introduces the concept of assessing the built environment. In this chapter we look to understand what it is, how it measures sustainability, and characteristics and limitations it has. The early sections describe the importance of sustainable construction and material selection, highlighting the environmental challenges we face today and how assessments can potentially make a difference. The main body of the chapter includes a selection of commonly adopted assessment methods and how they function. A particular section is devoted to other types of industry tools. Finally, we look at common features shared between assessments and how the marketplace delivers in response to these collective measures. *Learning outcomes*: on successful completion of this chapter, readers should be able to: (1) appreciate how building construction and operation impacts on the environment, (2) have a general knowledge of how building assessment methods operate, their differing characteristics, applicability, and limitations, and (3) understand how the marketplace reacts to such measures when engaging with assessment methods

**Keywords** Building assessment · Sustainable construction/operation

## 18.1 Introduction

The objective of this chapter is to bring together the current thinking on how we define and measure sustainability in the built environment. It aims to concisely lay out the key issues in what, at first sight, can be a large and complex area.

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The reader needs to be aware that this is a rapidly, and rightly so, changing field and one that cannot easily be summarized in a few pages; it is therefore merely an introduction to this subject.

Although, one is perhaps familiar with the three typical components of sustainability (i.e., environmental, economic, and social) as part of an environmental assessment, as society steps further into the practise of implementation it belies how complex and far reaching this debate is; embracing science, economics, politics, ethics, and engineering, while touching upon individuals or communities in both personal and work lives. Fortunately, the practise of assessing the built environment (component, building, site, and neighborhood) has devised practical ways of addressing sustainability measurement and delivery by focusing on the key issues in terms of economic, environmental, and social and their impacts. As our understanding improves, this requires identification and reconciliation of all the key issues, which are inextricably interwoven.

If we are to ensure we create not only high performing buildings, but also ones that people want to live in it is imperative that we do so using 'metrics and not adjectives', and base our actions on science and evidence from the way we construct buildings and the way in which they perform.

In setting the scope of this chapter, it is important to be clear that it does not attempt to tackle the multitude of moral and ethical issues which arise but focuses on the issues that have an impact on human beings as set down in Table 18.1

## 18.2 Sustainability in Construction

Construction and its associated products not only underpin much of the UK's economic activity, but it also contributes approximately £100 billion to the UK's gross domestic product (GDP) (BERR 2008; ONS 2008). By comparison, manufacturing contributes 16 % of GDP, defence 4 %, and agriculture just 1 %. UK construction can be 'world class' with modern buildings that are more comfortable and efficient, use more natural lighting, are better ventilated, more flexible, cheaper to heat (and cool), and use significantly less energy than existing buildings. In addition, the characteristics and performance of most basic construction materials are now well understood and long lifetimes or durability can be achieved simultaneously with low maintenance costs.

The construction industry's success is further demonstrated by its substantial export earnings; some £10 billion per annum, arising particularly from the activities of constructors, engineers, and architects who deliver high-quality buildings and infrastructure projects worldwide. Its design skills alone generate around £3.8 billion export income per annum through high-profile projects. This standing and economic strength is achieved through the education and training of first-class design and construction professionals, underpinned by a substantial manufacturing base and a skilled workforce. Cutting edge technology and continuous improvement cycles in construction have been maintained primarily by:

**Table 18.1** Key environmental issues

| Issue | Importance to humans |
|---|---|
| Climate change | Human activities have both direct and indirect impacts on the climate, which affects weather patterns which in turn has an impact on economic and social activity, as well as health, well-being, safety, and demands for resource use. |
| Global warming | The earth's atmosphere acts as a greenhouse, trapping solar energy and heat. Without this process life could not exist on the planet. It is widely accepted that human activity, in particular the emissions of $CO_2$, is acting to intensify this process, resulting in a gradual warming of the atmosphere. This is expected to result in significant climate change, although the level and nature of this change will have considerable variation regionally. Global warming will cause significant warming of the oceans resulting in notable sea level rises, which could have major impacts on many centers of population and may alter the earth's albedo (i.e., the extent to which it reflects light from the sun). |
| Carbon emissions | Carbon emissions are a major cause of climate change, leading to major impacts on all aspects of human welfare. |
| Energy use | Energy is essential to human well-being, but unless its use is in balance with the capacity of the planet to absorb carbon emissions and waste heat, it will lead to major impacts on all aspects of human welfare. There are also related social and economic issues of energy security. |
| Global dimming | Global dimming is the reduction in irradiance at the earth's surface caused by absorption of radiation by particulates such as sulfate aerosols. It is thought to affect the world's hydrological cycles and create a cooling effect, which may have partially masked climate change. This has been linked to problems with water supply, crop failure and desertification. |
| Water resources | Water is essential to life, but its use must be in balance with local resources for its provision and the processes in place for wastewater treatment. |
| Water availability | Human activities can reduce the availability of water through overuse and increased surface runoff, which can have significant impacts on human health and economic activity. There are also related social issues. |
| Over-use | Overuse can lead to: damage to ecosystems; loss of biodiversity; desertification; soil erosion; habitat destruction; risks to water security; and accelerated climate change due to energy use for purification, pumping, and desalination processing. |
| Flooding | Flooding results from a loss of absorption capacity which can directly result in damage to aquifers, property, and economic activity. It can also result in contamination problems. Rapid runoff prevents replenishment of groundwater aquifers and hence leads to supply problems. |
| Salinization | Over-extraction of groundwater for human use can lead to ingress of saline water into aquifers from the sea, which effectively prevents its continued use through increasing mineral levels. In addition, changes in rainfall can significantly alter the salinity of both groundwater and seawater, impacting on human health and biodiversity. |
| Water security | Overuse and flooding can reduce water security. This has potentially serious political and health implications for many populations. |

(continued)

**Table 18.1** (continued)

| Issue | Importance to humans |
|---|---|
| Pollution | Pollution can significantly impact on human health, ecosystems, and amenity value as a result of toxicity and acidity into the natural environment. It can also result in physical damage to property and infrastructure. The disposal of waste is a major cause of pollution to land, water, and air and its disposal can have major impacts on human and ecological health. |
| Water pollution | Water is essential to human life and natural ecosystems, but runoff from industry and agriculture can damage both surface water and groundwater, and in some cases making it toxic. |
| Marine pollution | Agricultural, industrial, and human waste pollution of the sea has more complex interactions than simple freshwater pollution, but in addition to loss of fish stocks, it may be implicated in a loss of the ocean's capacity to absorb carbon—hence accelerating climate change. |
| Air pollution | Pollutants are linked to rises in pulmonary disorders, and corrosive pollutants, such as ozone and sulfurous oxides have damaged forests, fisheries, and buildings. Some are leading to global dimming. |
| Acid rain | Emissions of nitrous and sulfurous oxides from the burning of fossil fuels result in high levels of acidity, which are carried to ground level in precipitation. This 'acid rain' can cause severe damage to the built environment and ecosystems, as well as having major impacts on the productivity of agriculture and forestry. |
| Soil pollution | Various industrial and agricultural by-products can damage ecosystems and the food-generation capacity of soil, in some cases making it toxic. |
| Soil erosion/ flooding | Over-development of land can lead to heavy surface water runoff, causing flooding, pollution, and soil erosion. These can be mitigated by appropriate construction and provision of features designed to reduce flows and retain water (sustainable drainage) or to retain soil through physical barriers, hedges, and other planting. |
| Land take | Development often diverts land from other economically important activities or from leisure use. |
| Land remediation | Reuse of land potentially brings it back into productive use and reduces the demands on other land resources. |
| Biodiversity | Many of our technological advances, especially in the fields of agriculture, medicine, and alternative energy, depend on natural resources to provide a starting point. The loss of plant and animal species limits the future potential for medical and agricultural research. More intensive agriculture and development can have significant impacts on biodiversity. |
| Habitat destruction | Development can be very damaging to natural habitats. It impacts on the provision of leisure facilities and can lead to a loss of local biodiversity. Development can be carried out in a manner that limits damage or enhances ecological value. |
| Damage to ecosystems | Ecosystems are dynamic relationships between plants, animals, microorganisms, and the nonliving environment. They can play many roles including pollination, protection against soil erosion, air quality improvement, climate regulation, water purification and regulation, waste treatment, and biological and disease control. While they often have some functional redundancy, serious damage or destruction of ecosystems can have major impacts on human health, agriculture (crop yield), climate, and infrastructure. |

(continued)

**Table 18.1** (continued)

| Issue | Importance to humans |
|---|---|
| Resource depletion | Almost all resources that we currently depend on are finite or otherwise limited. Loss of scarce resources could lead to a loss of technological capability and have harmful results on industry, economics, and society in the future. |
| Ozone depletion | Although, various protocols have agreed that chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) should no longer be produced, black market trading continues to be a problem, especially with existing systems, and is delaying the 'healing' of the ozone layer with all its adverse implications for human health and the natural environment. |
| Desertification | Reduction of land available to support human life leads to hunger, migration, and pressure on economies. |
| Population | Population density has a major effect on demands for resources, including water and energy, and ecosystems, land use, and pollution levels. |

innovative manufacturers and constructors; codes and standards; innovation underpinned by many years of applied research; technology and innovation organizations working collaboratively with government; general industry, and academic institutions.

Unfortunately, the high economic contribution of the construction industry and the built environment comes at high environmental cost with, for example, buildings accounting for around 45 % of total UK greenhouse gas emissions and production of materials accounting for a further 10 % (ONS 2008). While what constitutes sustainability is a complex issue requiring solutions from the fields of science, engineering, politics, economics, sociology, and ethical values, the UK has played a leading role in setting the pace for sustainable construction since 1990, when the BRE Environmental Assessment Method (BREEAM) (BRE 2009), the world's first environmental assessment method for buildings, was launched. BREEAM is the collaborative result of many years' development of codes, standards, and toolkits by a network of organizations working with government, industry, and universities. In addition to the growing BREEAM family of standards, significant standards and tools include:

- CEEQUAL—the Civil Engineering Environmental Quality Assessment and Award Scheme;
- DQI—the Construction Industry Council's Design Quality Indicator;
- FSC—the Forest Stewardship Council.

Company tools such as Arup's SPeAR® (ARUP 2000) have also done much to advance knowledge. These codes and standards are designed to work with some or all parts of the UK's construction industry and at different stages in a construction product's life cycle (i.e., Masterplanning, New Build, In use, Refurbishment, and End of life). An overview of these and other publicly available tools is given later in this chapter, while some of the best known international codes and standards are also described later in this chapter.

Regulatory and voluntary mechanisms should work together to encourage optimal performance. Regulation is a powerful and necessary tool for achieving sustainability targets, but it can only set a common base. Over time this base is raised to achieve major changes, but this must be at a pace that the majority of the industry can deliver. Voluntary codes and standards provide a means of encouraging industry leaders and innovators to go further and faster. An example of the steady 'ramping up' of standards in the context of the UK is the Department of Communities and Local Government's (CLG) proposed 'road map to zero carbon domestic buildings'. Regulatory standards vary greatly across the world. This is the case even with highly developed economies such as those of Western Europe (including the UK) and North America. These variations in the statutory baseline arise from physical differences such as climate and construction technologies as well as cultural and political differences.

Construction and the management of the built environment involve many stakeholders. Relationships are complex and the tools, standards, and guidance are usually focused on parts of this network. In reality, all stakeholders are impacted to some degree by most of the initiatives covered in this topic within this chapter, but this is often indirect. Any driver of change needs to target specific stakeholders while considering the impacts on others less directly affected. In general, a 'one size fits all' tool is unlikely to meet any individual stakeholder's needs in a robust manner.

As a means of reference, Table 18.2 can be used to access the home pages of departments and organizations that manage the various regulations, standards, schemes, and codes that are mentioned throughout this chapter.

## 18.3 Tools for Measuring Sustainability

Over the past 20 years or so, industry has experienced the launch of many tools and measures to usher its work practices toward a sustainable path. With the introduction of mandatory and voluntary building assessments, coupled with schemes and international standards managed by various organizations and councils, building performance and construction (worldwide) can be measured and compared to facilitate an accelerated route to sustainability. This section reviews a selection of the most widely recognized tools.

### *18.3.1 BREEAM—BRE Environmental Assessment Method*

BREEAM was the first, and continues to be the world's leading rating and assessment method for buildings. Launched in 1990, BREEAM consists of a suite of integrated tools, developed from many years of research, scientific, and market analysis. It assesses the environmental impacts of buildings in terms of: energy; transport; health and well being; water; materials; waste; pollution; land use and site

**Table 18.2** Websites for UK regulations and voluntary codes

Websites for UK regulations and voluntary codes

| Legislation, regulation, voluntary codes, and standards | Website address |
|---|---|
| All enacted UK legislation (available from the Office of Public Sector Information; part of the National Archives) | www.opsi.gov.uk |
| BREEAM family of assessment methods | www.breeam.org |
| CEEQUAL | www.ceequal.com |
| Code for Sustainable Homes (CSH) | www.communities.gov.uk |
| Considerate Constructors Scheme | www.considerateconstructorsscheme.org.uk |
| Construction, Design and Management (CDM) Regulations 2007 | www.hse.gov.uk |
| Construction Products Directive | www.communities.gov.uk |
| Control of Noise (codes of practice for construction and open sites) (England) Order 2002 | www.opsi.gov.uk |
| Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) | www.cites.org |
| Design Quality Indicator (DQI) | www.dqi.org.uk |
| Disability Discrimination Act 1995 | www.dwp.gov.uk |
| Energy Performance of Buildings Directive—Energy Performance Certificates (EPC) | www.communities.gov.uk |
| Environmental Profiles (Life Cycle Assessment) | www.greenbooklive.com |
| European Directives (all published in the Official Journal of the European Communities) | http://eur-lex.europa.eu/JOIndex.do |
| European Emissions Trading Scheme (2005) | http://ec.europa.eu/environment/climat/emission.htm |
| Hazardous Waste Regulations (England and Wales) 2005 (other regulations apply in Scotland and Northern Ireland) | www.opsi.gov.uk |
| Home/Building Information Packs Regulations (HIP/BIP) | www.communities.gov.uk |
| Household Waste Recycling Act | www.defra.gov.uk |
| List of Wastes Regulations (England) 2005 (other regulations apply in Wales, Scotland, and Northern Ireland) | www.opsi.gov.uk |
| Management of Health and Safety at Work Regulations 1999 | www.opsi.gov.uk |
| Registration, Evaluation, Authorization and restriction of Chemicals (REACH) | www.hse.gov.uk/reach |
| Regulatory Reform (Fire Safety) Order 2005 | www.opsi.gov.uk |
| Restriction of Hazardous Substances Directive (ROHS) | http://www.bis.gov.uk/ |
| Framework standard for the Responsible Sourcing of Construction Products, BES 6001 (available from BRE Global Ltd) | www.bre.co.uk |

(continued)

**Table 18.2** (continued)

Websites for UK regulations and voluntary codes

| Legislation, regulation, voluntary codes, and standards | Website address |
|---|---|
| Secured by Design | www.securedbydesign.com |
| SMARTWaste | www.smartwaste.co.uk |
| Standards being developed under European Commission Mandate M350—Integrated Environmental Performance of Buildings (European platform on Life Cycle Assessment) | http://lca.jrc.ec.europa.eu |
| Standards published by the International Standards Organization (ISO), including ISO 9000 and ISO 14000 | www.iso.org |
| UK government Planning Acts, Building Acts, and all their supporting regulations, policy statements, and policy guidance | www.planningportal.gov.uk |
| Waste Electrical and Electronic Equipment (WEEE) Directive and Regulations | http://www.bis.gov.uk/weee |
| Waste regulations pertaining to the built environment in use (various) | www.opsi.gov.uk |
| Water fitting regulations | www.defra.gov.uk |
| Workplace (Health, Safety, and Welfare) Regulations 1992 | www.opsi.gov.uk |

ecology; and management. Since its launch, the method has been regularly enhanced to ensure that it reflects current regulations, standards, and industry practices, while providing an incentive to maximize the outcome of a construction project. In 2011, BREEAM committed to widening the group of stakeholders involved in its future development, both strategically and at the local level. In doing so it aims to be a vehicle for design support, as well as assessment, across all building life cycle stages and infrastructure, including the masterplanning of large-scale developments. This places BREEAM in the forefront of sustainable development, with local schemes, processes, science and governance cooperating internationally under an overarching framework defined by core standards and core science. Figure 18.1 shows the operating roles and relationships within BREEAM.

This development now includes operation and management, through BREEAM in use, and broader infrastructure and planning issues, through BREEAM Communities. The assessment method covers all types of buildings through *sector-specific* versions. This provides a filtering of criteria to ensure relevance to the project in hand, while maintaining a common overall standard.

Since the introduction of BREEAM in 1990, the standard has been kept ahead of, but in step with, UK sustainability regulations and ramped up as fast as the market will bear (BRE 1990–2008). As a voluntary standard, BREEAM must keep in step with the economic costs of higher sustainability and property market expectations. Working closely with UK government, BREEAM has also helped test market impacts of its policy imperatives.

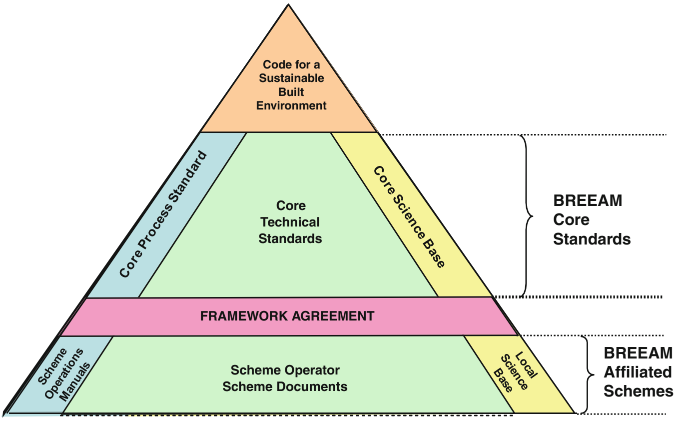


**Fig. 18.1** Operating roles and relationships within BREEAM

Post-construction assessments are now mandatory for final certification. To encourage designers and builders to innovate and enable lessons learned to be promulgated; an 'Outstanding' rating for exemplar buildings has also been introduced with 'Innovation' credits to recognize beneficial sustainability aspects within the design that are not covered under the standard criteria. Technical experts from BRE, academia, and industry stakeholder groups develop the standards, but suggestions for improvement are welcomed from anyone. With formal, a formal review process through a standing panel of experts.

All BREEAM assessments are carried out under licence by non-BRE companies and personnel—some 10,000 non-BRE personnel are thought to earn some, or all of their living through BREEAM in the UK.

BREEAM is recognized, even in popular publications, as a powerful force for greener building (Henson 2006).

While BREEAM is owned by the research and education charity *The BRE Trust*, the content, and operation of BREEAM is overseen by a *Governing Board* and standing panel dominated by independent stakeholders who neither pay, nor are paid, for the privilege and responsibility. The development and operation of BREEAM along with the training, operation, and quality management of the assessor network are all accredited by the United Kingdom Accreditation Service (UKAS) to ensure independence, impartiality, probity, and robustness.

### *18.3.2 LEED—Leadership in Energy and Environmental Design*

LEED was launched in 1998 and adapted from the UK BREEAM method to meet the needs of the USA. It was developed by the US Green Building Council (USGBC) to improve the way that the US construction industry addressed sustainability by providing a simple, easy-to-use label.

Each version has four ratings: (1) *Certified* (26–32 points); (2) *Silver* (33–38 points); (3) *Gold* (39–51 points); and (4) *Platinum* (52–69 points)—based on the total number of credits that are achieved together with baseline performance in key areas. In addition, a number of mandatory requirements must be achieved before a rating can be awarded. These are not scored in the method.

LEED currently has versions covering the following:

- New Commercial Construction and Major Renovation projects;
- Existing Building Operations and Maintenance;
- Commercial Interiors projects;
- Core and Shell Development projects;
- Homes;
- Neighborhood Development;
- LEED for Schools;
- LEED for Retail;
- LEED for Healthcare (under development);
- LEED for Labs (under development).

The current LEED NC (New Commercial Construction and Major Renovation) projects were launched in 2005. This version is used throughout the design and construction phase, but the actual label (certificate) is only available once the construction is completed. The project team compiles the documentation required for the assessment. A trained assessor is therefore not required, although there is a credit available for appointing a LEED Accredited Professional (LEED AP) as part of the design team. Once all the documentation has been compiled, it is submitted to USGBC, which reviews the evidence and calculates the score. The project team has the opportunity to dispute the final score prior to USGBC issuing a certificate and a plaque with the rating on it.

There are no explicit weightings included within LEED. Individual credits are all worth one point (and where there are multiple performance levels each level is worth one point). The value of each issue is therefore dependent on the number of steps in the assessment criteria relating to actions that the project team can take rather than any measure of a reduction in environmental impacts resulting from the actions taken. Currently, LEED uses a checklist approach to assess the embodied impact of the materials.

LEED is developed by USGBC through a committee structure with representatives drawn from USGBC's membership. This allows representation from a wide range of sectoral interest groups. Until recently, all certification has been carried out by USGBC. To overcome growing capacity difficulties, USGBC has recently established its own independent certification body, which in turn accredits a small number of external bodies to carry out certification under the scheme alongside USGBC. USGBC is accredited by the American National Standards Institute (ANSI) as a standards developer (which covers the technical development of the standards). This accreditation does not cover the operation of the scheme. Technical requirements relate to US standards, which vary from those in many other countries. This makes a direct comparison of credits between schemes difficult.

### *18.3.3 Green Star*

The first version of Green Star was developed for Australia in 2003 in a partnership between *Sinclair Knight Merz* and BRE. As BREEAM was used as the basis of the Green Star methodology, the two methods are very similar. However, adaptations have been made to reflect the various differences between Australia and the UK, such as the climate, local environment, and the standard practices in the construction industry. The environmental weightings have been re-evaluated to the Australian context using a similar approach to that adopted in the UK. Since the initial launch of Green Star, the Green Building Council of Australia (GBCA) has also adapted the assessment methodology to make the delivery mechanism more akin to the LEED approach, where data are collected by the design team with verification prior to certification by GBCA.

There are currently seven versions of the methodology:

Green Star—Office Design v3
Green Star—Office As Built v3
Green Star—Office Design v2
Green Star—Office As Built v2
Green Star—Office Interiors v1.1
Green Star—Retail Center v1
Green Star—Education v1
Green Star—Communities

Green Star can be used by any member of a design team or wider project team to provide a self-assessment. No resulting score can be publicized unless the Green Star assessment is certified by GBCA. A third-party assessment panel is used to validate the self-assessment rating, then recommend or oppose the final Green Star rating. Certification will only be awarded if a project achieves a score of at least 45 (four stars).

The following Green Star-certified ratings are available:

Four-star rating (score 45–59) signifies ‘best practice’
Five-star rating (score 60–74) signifies’Australian excellence’
Six-star rating (score 75–100) signifies ‘world leadership’.
Last, Green Star is developed and operated under a similar governance structure to LEED.

### 18.3.4 CASBEE—Comprehensive Assessment System for Building Environmental Efficiency

CASBEE was launched in 2004 by the Japan Sustainable Building Consortium (JSBC). The methodology is used to calculate a Building Environmental Efficiency (BEE) score that distinguishes between environmental load reduction and building quality performance. This was adapted from the approach first developed by the International Initiative for a Sustainable Built Environment (IISBE) in the form of *GBTool*. There are four versions of CASBEE: (1) CASBEE for Pre-Design; (2) CASBEE for New Construction; (3) CASBEE for Existing Buildings; and (4) CASBEE for Renovation.

Under CASBEE, all building permit applicants must submit the required data, part of which is displayed on a public website. CASBEE is marketed primarily as a 'self-assessment check system' to permit users to raise the environmental performance of buildings under consideration. It can also be used as a labeling system, if the assessment is verified by a third party.

CASBEE is a complex calculation methodology. It uses weightings to balance the value of addressing issues with the number of measures recognized within the method. The more measures available to improve environmental performance, the more credits can be developed, but this does not necessarily reflect the environmental impact of addressing the issues. However, the weightings applied to CASBEE are much more complex than BREEAM, LEED, or Green Star.

Weightings are applied to each category, which include 'indoor environment', 'outdoor environment onsite', 'energy' and, 'resources and materials'. In each category, there are headline issues such as 'serviceability', 'lighting and illumination', and 'building thermal load' to which another layer of weightings is applied. Under these headline issues, there are individual issues including'noise', 'ventilation', and 'use of recycled materials', which are also weighted. A final layer of weightings is applied to the sub-issues grouped under each of the individual issues. The sub-issues include 'ventilation rate', '$CO_2$ monitoring', and 'adaptability of floor plate'. All the issues are split into two basic types: *quality* measures (Q) and *load reduction* measures (LR). Once the assessment has been carried out, the final BEE score is calculated.

### 18.3.5 CEEQUAL—Civil Engineering Environmental Quality Assessment and Award Scheme

CEEQUAL provides a generic assessment of the environmental quality of the design and construction of major civil engineering projects, and as such complements BREEAM, which focuses on buildings and communities. Developed by a number of major industry partners under the auspices of the Institution of Civil Engineers (ICE), it is based on the structure of BREEAM and was launched in 2004.

The method promotes consideration of sustainability issues throughout the procurement process and covers the following areas:

- Project management;
- Land use;
- Landscape;
- Ecology and biodiversity;
- The historic environment;
- Water;
- Energy and carbon;
- Use of materials;
- Waste;
- Transport;
- Effects on neighbors;
- Relations with the local community and other stakeholders.

CEEQUAL focuses on the actions undertaken to ensure that environmental quality is built into the design and construction processes. Unlike BREEAM, it does not reward or benchmarked against specific measured performance levels as these vary between project types. Current versions of the method are designed for use on projects with clearly defined boundaries. A term contracts version of the scheme is being developed that will be aimed at the assessment and recognition of environmental performance on maintenance or minor works over a period of time.

As with BREEAM, CEEQUAL builds on the current regulatory framework and provides guidance and environmental good practice in civil engineering projects. It provides a protocol for assessing, benchmarking, and 'labeling' the sustainability performance of such projects.

Within CEEQUAL, six awards are available to recognize the roles of different stakeholders and stages in the procurement of a project: (1) Whole Project Award (WPA), applied for jointly by or on behalf of the client, designer, and principal contractor(s); (2) WPA with an Interim Client & Design Award, where the stage in the design process at which the interim assessment is undertaken can be chosen by the applicant to best suit their needs and procurement process; (3) Client and Design Award, applied for jointly by the client and designer before construction has started; (4) Design Award, applied for by the principal designer; (5) Construction Award, applied for by the principal contractor(s); and (6) Design and Build Award, for project teams that do not include the client on design-and-construct and other partnership contracts.

Assessments are carried out internally within a range of procurement design or construction organizations. To ensure independence, these assessments are independently verified by verifiers trained and licensed by CEEQUAL Ltd. The method includes a range of credit areas that lie outside the scope of specific projects. For this reason, the assessment process includes a scoping stage, where these credits can be removed if they are not relevant. The assessment process is as follows:

- Scoping—assessor and verifier;
- Assessment—assessor;
- Submission—assessor;
- Verification—verifier;
- Certification—CEEQUAL Ltd.

The scheme is owned and operated through CEEQUAL Ltd, to which *CIRIA* and *Crane Environmental* are contracted to administer the company and Scheme. CEEQUAL Ltd is supported by, amongst others, ICE, the Civil Engineering Contractors Association (CECA), and the Association for Consultancy and Engineering (ACE). CEEQUAL is not covered by any form of external accreditation.

### *18.3.6 Green Globes*

Green Globes is an environmental assessment and certification scheme based on BREEAM and includes self-assessment with independent third-party verification. It is owned and operated by the Building Owners and Managers Association (BOMA) in Canada and the Green Building Initiative (GBI) in the USA. The tool is available through subscription online. The service is designed primarily to provide interactive support and assessment to medium and small developments, although it is also widely used by property developers and managers on larger developments. The method applies to both new build and existing buildings. Processes and developments are accredited by the ANSI.

### *18.3.7 UNEP—United Nations Environment Programme*

UNEP is the United Nation's (UN) designated entity for addressing environmental issues at the global and regional level. The UN confers power upon a designated entity in relation to the administration of UN sanctions and enforcement laws. Its mandate is to coordinate the development of environmental policy consensus by keeping the global environment under review and bringing emerging issues to the attention of governments and the international community for action. The mandate and objectives of UNEP emanate from UN General Assembly resolution 2997 (XXVII) of 15 December 1972; Agenda 21, adopted at the *UN Conference on Environment and Development* (the Earth Summit) in 1992; the Nairobi Declaration on the Role and Mandate of UNEP, adopted by the UNEP Governing Council in 1997; the Malmö Ministerial Declaration and the UN Millennium Declaration, adopted in 2000; and recommendations related to international environmental governance approved by the 2002 World Summit on Sustainable Development and the 2005 World Summit. The UNEP Governing Council reports to the UN General Assembly through the *Economic and Social Council*. Its 58 members are elected by the General Assembly for four-year terms.

UNEP is currently running a sustainable *Buildings and Construction Initiative*. This group has a remit to: (1) promote improved support mechanisms for energy efficiency in buildings under the Kyoto Protocol; (2) identify and support the adoption of policy tools which use a life cycle approach to investment within the building sector; and (3) develop benchmarks for sustainable buildings.

## *18.3.8 International Standards*

### 18.3.8.1 ISO 14001—Environmental Management Systems

*International Standard ISO 14001* (British Standards Institution 2004) specifies requirements for an Environmental Management System to enable an organization to develop and implement a policy and objectives which take into account legal and other requirements to which the organization subscribes, and information about significant environmental aspects.

Because the standard is about how a company manages and improves its processes, ISO 14001 does not enable benchmarking and comparison between different buildings, processes, and organizations. However, it does provide a useful framework for managers designing their systems.

### 18.3.8.2 European Commission Mandate M350—Integrated Environmental Performance of Buildings

The European Commission has mandated the European Committee for Standardization (CEN) to develop a suite of standards (*Mandate M350*) for the 'integrated assessment of environmental performance of buildings' based on a life cycle assessment (LCA). The standards are intended to provide a voluntary method for delivery of environmental information that supports the construction of sustainable works; including new and existing buildings (not all construction works will be included). Specific areas covered include frameworks for the assessment of:

- environmental performance (prEN15643-2);
- social performance (prEN15643-3);
- economic performance (prEN15643-4); and
- a general framework integration of these (prEN15643-1).

These operate alongside rules for calculating and reporting:

Environmental Product Declarations (EPDs) for construction materials (prEN15804), which use a methodology similar to that used for BRE Environmental Profiles, and aggregated data from EPDs and other information. For example, energy performance data derived from National Calculation Methodologies such as the

Standard Assessment Procedure (SAP) (BRE 2005) and the Simplified Building Energy Model (SBEM) (BRE 2006) to produce a table of environmental impacts for a building throughout its whole life (similar in approach to the methodology used in BRE's ENVEST tool).

The standards will only describe methodologies for assessment; they specifically do not provide or attempt to prescribe benchmarks or levels of performance.

### *18.3.9 World GBC—World Green Building Council Movement*

*World GBC* is a union of national councils whose mission is to accelerate the transformation of the global built environment toward sustainability. The current member nations of the council represent over 50 % of global construction activity, and reach more than 15,000 companies and organizations worldwide. Its members are leading the movement to help globalize environmentally and socially responsible building practices. It aims to rapidly build an international coalition that represents the entire global property industry.

World GBC provides leadership and a global forum to accelerate market transformation from traditional, inefficient building practices to new-generation, high-performance buildings. This is a critical response strategy for cities and countries worldwide to their national and international commitments to reduce carbon emissions and redress other environmental impacts.

World GBC is a business-led coalition. Green building councils are consensus-based, not-for-profit organizations with no private ownership, and diverse and integrated representation from all sectors of the property industry. They see business as a powerful solution-provider, and are working to improve frameworks that harness business's ability to deliver.

### *18.3.10 GRI—Global Reporting Initiative*

*GRI*'s vision states that all organizations should report on their economic, environmental, and social performance as routine, comparable to financial reporting. GRI is a not-for-profit entity supported by members of their stakeholder networks.

The *GRI Sustainability Reporting Guidelines* form the basis of a *Sustainability Reporting Framework* that guides and supports organizations in identifying, measuring, and disclosing their sustainability performance; it also provides stakeholders with a universally applicable, comparative framework, providing the opportunity to benchmark performance, and provide clarity in understanding disclosed information. The Reporting Framework provides transparency and accountability in all sizes of organizations and sectors across the world.

GRI is a worldwide, multi-stakeholder network with a robust governance structure to ensure consistency and transparency. Members from the business community, civil society, workers, investors, accountants, and all others collaborate to develop and improve the tools and guidance through consensus-seeking approaches. The multi-stakeholder approach ensures the credibility and trust required of a global disclosure framework.

### *18.3.11 Framework for RSM Standards*

Within the sustainability arena, globalization of the supply chain is making it increasingly difficult to ensure that procurement takes into account all legal requirements together with environmental, social, and economic considerations. There is therefore considerable demand for responsible sourcing standards operated by third parties to enable procurement to take into account major legislative and other requirements, as well as economic, environmental, and social issues such as employment, safety, child labor and effects on local communities. Not surprisingly, there is now a proliferation of such standards on the world stage covering some or all of the major issues, which are mostly operated by first- or second-party certification schemes.

One example is BRE Global's framework standard BES 6001 (BRE 2008a, b). BRE, together with the Construction Products Association (CPA), the British Standards Institution (BSI), and others have developed and published a Framework Standard for the *Responsible Sourcing of Construction Products BES 6001* (BRE 2008a, b). Key players in the construction materials and components sector are currently working with BRE to develop BES 6001-compliant, sector-specific standards.

### *18.3.12 Code for Sustainable Homes*

The Department of Communities and Local Government (DCLG) launched the Code for Sustainable Homes (CSH) (DCLG 2008) in December 2006, with the actual method introduced as a voluntary standard in April 2007. This method is based on BRE's *EcoHomes* version of the BREEAM methodology adapted to relate closely to Building Regulations and government policy. The method is owned by CLG and operated on their behalf by BRE Global, which also acts as technical advisor. BRE Global is contracted to operate the scheme and also license other operators to offer certification under the scheme.

The method operates using a performance-based system which awards points for certain standards achieved within nine categories including: energy and CO2 emissions; water; materials; surface water runoff; waste; pollution, health, and well-being; and management and ecology.

Six different star rating levels can be potentially awarded. Since October 2007, Level 6 has required a net zero carbon solution achieved through a private wire arrangement to bring the Code for Sustainable Home (CSH) in line with the UK

Treasury's definition of a zero carbon dwelling, used to determine eligibility for the exemption of stamp duty land tax. This definition has resulted in concerns over its practicality as it precludes any use of community or off-site-based energy systems. Opposition has been met my *BRE Global*, the UK Green Building Council (UKGBC) and others, who have recommended that the definition be expanded to encompass the use of such systems, once cost-effective on-site options have been exhausted (where they can be considered additional to existing commitments to renewable energy provision).

### *18.3.13 Environmental Profiles*

Demand for advice and information on the environmental impacts of products in the early 1990 s led to an EU eco-labeling scheme, which was originally intended to apply to both consumer and construction products. Work by BRE demonstrated that the EU regulation was unsuitable for building products where it is essential (but very difficult) to take the application and whole-life performance into account. This led to further work by BRE with the CPA to develop an environmental profiling methodology suitable for building products. This was initially based on the *SETAC* principles of LCA (see Sect. 3.17), but subsequently BRE Global has been working to incorporate and ensure compatibility with *ISO standards* and *European Commission Mandate M350*.

LCAs of manufacturing processes apportion energy, water, waste and raw material costs, and impacts to the production of a range of products and co-products. While this sounds quite simple, there are lot of contentious issues relating to how these inputs and outputs are calculated and allocated to co-products, how waste is defined and how future recycling should be accounted for. For example, the production of iron for the steel industry also produces slag, some of which can be used as fill, aggregate, and in blended cements. If environmental impact allocations are based on the mass of the resulting products, most of the impacts become associated with the aggregate. For this reason, value allocation has become more common, but this in turn becomes very complicated because of rapid changes in prices in the commodity market. In the absence of a clear basis for calculation, it is vital that there is transparency in the rules and education of specifiers in the use of Environmental Profiles and LCA data.

As previously mentioned, LCA is complex, and the science and economics are still being developed and debated. To make the results of the work accessible, BRE Global has collaborated with the CPA and others to produce Environmental Profiles in a standardized form using standard assumptions and algorithms, which enable specifiers to identify the major environmental impacts of a product at the point where the product leaves the factory gate. Specialist practitioners can use the data and different calculation algorithms to assess impacts under different conditions and also using different allocations of environmental weightings.

### 18.3.14 DQI—Design Quality Indicator

The Design Quality Indicator (DQI) is a process for evaluating the design quality of buildings; it can be used by everyone involved in the development process to contribute to improve the quality of built environment. DQIs provide a generic toolkit that can be used with all types of building. There is also a version specifically developed for school buildings. DQIs provide a framework for understanding quality priorities, setting targets, and monitoring performance against them to evaluate design quality. They do not set specific performance levels, but provide an effective self-assessment process for use within the design process. Figure 18.2 shows the three key elements of DQI—build quality, functionality and impact, and their associated attributes.

The DQI process revolves around a workshop where the facilitator and design team members develop a set of project-specific targets against each of the DQIs. These targets are used to inform the briefing, design, or management process. There is a post-construction review process incorporated to allow follow-through of targets and feedback post-project. Training is provided for facilitators.

The development of DQIs was led by the Construction Industry Council (CIC) with input from a number of design consultancies and sponsors including the Commission for Architecture and the Built Environment (CABE), Office of Government Commerce (OGC), and Association of Building Engineers (ABE). The method is owned by CIC and is currently being adapted under licence in North America by DQI USA.

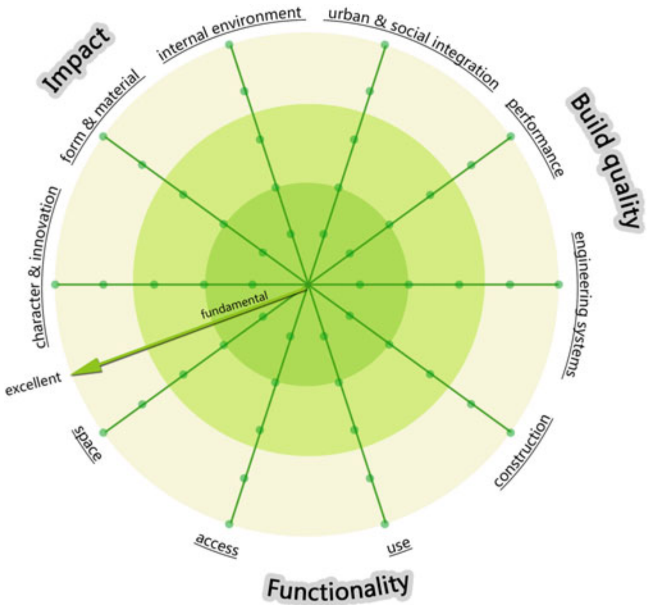


**Fig. 18.2** The DQI visualization (*source* CIC 2008)

### 18.3.15 The Green Guide to Specification

With the help of CPA and others, BRE has produced *The Green Guide to Specification* which provides simple environmental ratings of construction elements based on LCAs (Anderson et al. Anderson et al. 2002a). It is aimed at designers and specifiers who want to minimise the environmental impacts of buildings, and/or need to provide evidence for BREEAM assessments of buildings they are designing or procuring.

### 18.3.16 Envest

Software tool *Envest 2*, developed by the BRE (BRE 2012) enables specifiers to aggregate profile and whole-life data to better assess the environmental impacts of material and system specifications. Quoting from their website, the tool:

> …simplifies the otherwise very complex process of designing buildings with low environmental impact and whole life costs. Envest 2 allows both environmental and financial trade-offs to be made explicit in the design process, allowing the client to optimise the concept of best value according to their own priorities.

Using a web-based platform, tools like this are exceptionally useful to gauge the development of a project striving for a low environmental impact.

### 18.3.17 SETAC—Society of Environmental Toxicology and Chemistry

The Society of Environmental Toxicology and Chemistry (SETAC) was the first organization to publish a framework for LCA (SETAC 1991). LCA identifies and calculates all the inputs (energy and raw materials) and outputs (products and waste) for a defined product or system, providing information which can be used to interpret the effects on the environment.

SETAC is also a not-for-profit, worldwide, professional organization comprising individuals and institutions dedicated to the study, analysis, and solution of environmental problems, the management, and regulation of natural resources, research and development, and environmental education. SETAC's mission is to support the development of principles and practices for protection, enhancement, and management of sustainable environmental quality and ecosystem integrity. SETAC fulfills this mission through the advancement and application of scientific research related to contaminants and other stressors in the environment, education in the environmental sciences and the use of science in environmental policy and decision-making.

### 18.3.18 Supply Chain Management

Many parts of the construction materials supply sector are coming under increasing pressure to demonstrate sound environmental management at key stages in the supply chain. This is resulting in the development of standards and schemes for the responsible sourcing of materials (see Sect. 3.11) (BRE Global 2008a, b). This is a rapidly changing field, which started in the timber supply sector, where the Forest Stewardship Council (FSC) scheme was the first to provide a degree of robustness and rigor. Other schemes have followed suit in this sector, as a result of both marketplace and policy pressures, although their scope is not the same as that of FSC. These include the Programme for the Endorsement of Forest Certification (PEFC), Canadian Standards Association's (CSA), the National Standard for Sustainable Forest Management (NSSFM), and the Sustainable Forestry Initiative (SFI®).

### 18.3.19 FSC—Forest Stewardship Council

The Forest Stewardship Council (FSC) is an independent, non-government, not-for-profit organization established to promote the responsible management of the world's forests through certification against FSC standards. Its governance is founded on principles of participation, democracy, and equity, and its standards and policies are built on the following 10 principles:

- Compliance with laws and FSC principles;
- tenure and use rights and responsibilities;
- respect indigenous peoples' rights;
- foster community relations and uphold worker's rights;
- benefits from the forest;
- minimize negative environmental impact;
- implement a management plan;
- monitoring and assessment;
- maintenance of high conservation value forest plantations.

It is an international association whose members represent environmental and social groups, the timber trade and the forestry profession, indigenous people's organizations, responsible corporations, community forestry groups, and forest product certification organizations from around the world.

### 18.3.20 WWF One Planet Future

The World Wide Fund for Nature (WWF) has a campaign focus around the concept of a 'One Planet Future', where societal and individual demands on our planet are balanced with those of nature and the available resources, to ensure a sustainable and equitable future.

The vision is based on a reduction of impacts from current levels, which equate to roughly three times the carrying capacity of the planet (based on the assumption that the world's current population will strive to live as does the UK), requiring the equivalent of three planets to maintain our current levels of consumption.

Changes are required throughout our global society and WWF has a number of areas of work ranging from individual ecological foot-printing (WWF's *Ecological Footprint calculator*) to the concept of *One Planet Homes*. WWF lobbies governments and industry to implement system changes in the housing, transport, energy, and food sectors. Since 2003, WWF has been working with government, industry, and consumers to move the concept of sustainable homes from the fringes to the mainstream of the UK housing sector.

The campaign has proved highly successful in raising awareness and maintains a lasting and significant influence on the housing sector. WWF is now developing this work in the non-domestic sector.

## 18.4 Features of Assessment Tools

### *18.4.1 Balanced Scorecard*

Basic rating systems for environmental/sustainability impacts score a series of sustainability issues, giving each a unit weight and then adding the individual scores to obtain an overall rating. While simple to use, the disadvantage of such an approach is that an equal weighting factor is assigned to each assessment category, such as both an increment of energy performance and the provision of an ecological feature. In effect, a weighting is given to issues based entirely on the number of 'credits' attached to the issue, which makes it difficult to provide a balanced overall measure of performance while still encouraging best practice in each area. Other systems use a 'balanced scorecard' approach to summing the relative performance of each issue and then add those 'weighted' scores to obtain an overall score. This approach aims to use the relative weightings to ensure that issues of key importance, such as reduction in energy use, are made more important in the overall score than other more easily and cheaply achievable objectives such as the provision of a cycle rack. That is not to say that both are unimportant in their own right, but if rating systems are to be readily accepted they have to pass a 'common sense' test in terms of the relative impact of each issue on the overall sustainability rating. In BREEAM, for instance, the relative weightings are chosen in consultation with industry and specialists so users of the system are likely to feel that the relative importance 'feels right', given our current state of knowledge of relative costs and impacts.

### *18.4.2 Choice of Credits*

Simple systems require fixed performance levels to be achieved for each sustainability issue in order to achieve an overall rating. In criticism, this approach can be overly prescriptive. Such systems date rapidly provide far less value for money in terms of sustainability achieved per unit of expenditure compared with their more sophisticated counterparts.

More advanced rating systems allow designers flexibility in achieving a target overall score by allowing them to trade, say, higher performance in materials selection against lower performance in water consumption. This approach has been criticized for example, by theoretically allowing the achievement of a high overall score without taking significant steps to reduce $CO_2$ emissions. When combined with a balanced scorecard approach to scoring, this theoretical risk does not occur in practice, and such an approach is essential if industry is to achieve more sustainable outcomes without making them potentially unaffordable and in many cases unsustainable. This is because the relative costs, at any one time, of achieving each level of performance for each sustainability issue, are unknown. It is clearly important that practitioners retain the flexibility of choosing which points to achieve, and to what level, based on their creativity and the underlying costs, which vary over time and from market to market.

On consideration, it is clear that in some areas, particularly with $CO_2$ emissions, there is a very strong consensus that society needs to do much better than the regulatory minimum to achieve a high overall rating. For example, BREEAM 2008 sets minimum mandatory energy performance levels which correspond with each grade of award, although it allows full flexibility between other issues.

For system designers, the introduction of such 'fixed' requirements is a very challenging step as it requires a thorough understanding of not only the technological possibilities to achieve each fixed requirement, but also the attendant cost. This is a complex process in a dynamic marketplace, and one which requires sustained attention to maintain achievable fixed levels at relatively affordable costs, in line with technological and economic developments. Experience in the UK with the CSH (DCLG 2008) demonstrates that the inclusion of a significant number of policy-related mandatory issues, increases costs. For this reason, the number of 'fixed' requirements in advanced systems should remain very limited.

## 18.5 Delivery in the Marketplace

In order for the marketplace to offer advantages to companies who engage with the rating process, there has to be clear certainty that public claims regarding the sustainability rating of individual projects are justified. To achieve this, many systems require the award of a rating to be subjected to 'certification' by an independent body.

The simplest and most common approach is for the body that owns the standard to assess buildings and award an appropriate rating certificate. This can be very expensive and bureaucratic; however requiring the submission of large quantities of verifiable data is inherently inefficient as there is only one provider. This method has, in the past, encountered difficulty in adjusting capacity to meet market demand, although this can be mitigated through licensing multiple bodies to carry out the assessments. Although this process brings the assessment team into one place, it results in an increased burden to include a post-construction check. However, without a post-construction check there is considerable opportunity for ‘specification downgrading’ during construction.

A more flexible and accessible approach is to establish a network of individual licensed assessors who visit the design team and undertake assessments in the field, including a post-construction review to confirm that what is built, corresponds with initial construction specifications. In addition to lower intrinsic costs and less bureaucracy, this method allows individual assessors and assessor organizations to compete on service and price within the marketplace, ensuring best-value service delivery for clients. As many more assessors can be trained than are necessary at any one time, this approach copes well with an expanding market. Assessors also provide ‘real world’ feedback from design teams and constructors to system designers to ensure systems remain relevant and practical.

Experience shows that the mode and economics of delivery can be just as important to successful system take-up as the standard itself.

## 18.6 Conclusions

There are rapidly growing appetite for building assessments; specifically, methodologies which demonstrate the environmental performance of our activities, ranging from personal carbon foot-printing, to complex sustainability assessments for components, buildings, and entire cities. There are also rapidly growing demands to demonstrate sustainability in many aspects of the built environment, which result in a flood of claims and counter-claims together with the development of more and more standards, guidance, and rating methods. While much of this work is well founded and helpful in moving the agenda forward, the plethora of approaches introduces confusion and conflict in the marketplace and a lack of consistency in priorities and direction. This acts as a barrier to take-up and therefore in meeting the objectives that such initiatives set out to achieve. It must be recognized that the construction industry is diverse and has many, often conflicting, commercial and policy objectives which can disrupt or divert the drive to greater overall sustainability. Organizations are increasingly using the sustainability label to promote their products in an ill-informed marketplace with varying degrees of rigor and robustness. Despite this, the UK is ‘well ahead of any other country in terms of tackling this agenda’, a fact that strongly emerged from the 2008 *International Sustainable Building Conference* in Melbourne. No other country has the spread of focused initiatives in place, which are increasingly well linked to policy. The drive to overcome the deficiencies that undoubtedly exist in these methodologies must not result in a loss of this hard-earned experience, knowledge or commercial position. There is a need to consolidate and, where possible, simplify the 'toolbox' to improve understanding and take-up, but experience and quality must not be lost. Neither must there be a 'dumbing down' of targets or a loss of the focused message for different stakeholders.

It is hoped that the UK construction industry will continue to take the lead in sustainable building and find a way of delivering cost-effective and comfortable zero carbon buildings, well ahead of the government's targets. My view is that this is best achieved by taking a strategic overview of the requirements for a sustainable built environment, feeding this back into the development of existing leading tools that are operating in the UK. Working to create and strengthen links, metrics and promotion of sustainability labels and guidance, would have a dramatic effect both in terms of accessibility and in contributing to the development of government policy and industry strategies. The international dimension is paramount in taking this forward. Many client organizations, not to mention players in the construction and property sectors, do not restrict their operations to the UK or even European contexts. Increased international benchmarking and mapping of standards are vital. Drivers and needs vary considerably between climates, regulatory frameworks and, indeed, social and cultural priorities; consequently there is little scope for a 'one size fits all' approach.

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# Chapter 19
# Organizing for Sustainable Procurement: Theories, Institutions, and Practice

**Will Hughes and Samuel Laryea**

**Abstract** That construction procurement needs to be reorganized to make it more sustainable implies that there is a problem with the current situation. Starting from this assumption, an overview of construction procurement sets the scene for a discussion of some recent developments relating to organizational frameworks for sustainable construction procurement. Emergent theories dealing with sustainable procurement are considered. There is a plethora of standards and guidance documents for organizing sustainable procurement originating from a variety of organizations. These considerations form the context for approaches used in practice to achieve sustainable procurement. The chapter concludes with reflections on why current approaches are insufficient. It seems difficult to persuade clients to spend less money over the life cycle of their buildings. Future directions needed to translate sustainable procurement from rhetoric to reality include the development of suitable incentives and appropriate organizational structures. *Learning scope:* on successful completion of this chapter, readers will be able to: (1) explain construction procurement in relation to other kinds of organizational purchasing; (2) understand the specific reasons why construction procurement involves large numbers of different organizations in relation to phases in the life cycle of a constructed facility; (3) explain procurement as a business process based on incomplete and imperfect information; (4) understand the role of contracts and incentives in bringing about sustainable development; and (5) illustrate the range of policy guidance and standards that relates to construction procurement generally and sustainable procurement specifically.

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## 19.1 Introduction

Procurement is a commonly used term to describe the act of obtaining or buying something on behalf of someone else (Brookes 2003). Most large organizations have a procurement department that takes care of managing the buying processes for all kinds of supply that the organization uses. Indeed, this often extends to managing long-term relationships with key suppliers, in order to get the best deals combined with the best service. All of this is routine in most businesses. However, when it comes to the procurement of construction work, it is typically far too complex and unique for a procurement department to manage. That is one reason why some large organizations would also have a facilities management department in charge of the planning, design, construction, operation, maintenance, and disposal of construction projects.

'Construction procurement', in simple terms, often refers to the strategic process of how contracts for construction works are created, managed, and fulfilled (the ISO standard definition of construction procurement, British Standards Institution 2010a). But the term is usually used to embrace more than this. The procurement process in construction typically involves much more than mere purchasing, and its definition usually extends to funding and organizing construction at all stages of development (Hughes *et al*. 2006; British Standards Institution 2011).

## 19.2 Construction Procurement

Construction procurement requires input from a number of people. Some of these people are professionals with a detailed knowledge of construction processes and activities. Others are not. For example, there are many clients of construction work who may not have any knowledge at all of actual construction work. However, these clients would generally employ professionals such as designers, quantity surveyors, engineers, etc., to assist them with the acquisition of a construction project (Hughes and Murdoch 2001).

Architects develop their designs through conversations and research into the needs and wants of their clients. Research has shown that building design is not simply a discrete activity carried out by architects on behalf of their clients; rather, the design of a building emerges from a series of conversations and interactions with different potential *users* of the building (Luck 2007, 2009). Moreover, the architect in a building project is not usually one person, but an office constituted with a range of skills and experiences. Of course, the architect is not the only designer, since the task is split into a series of specialist areas such as structural design, building services design, quantity surveying, civil engineering, and so on. Indeed, the architect (or the civil engineer in infrastructure projects) may preside over a supply chain of designers, all of whom interact in the contribution of their various elemental parts of the design, which has to be coordinated in order for it to work. Each specialist design discipline may come from a different firm, and therefore each is tied to the project through a contract, or professional appointment terms that detail their roles, responsibilities, and remuneration. Additionally, design liability may be underpinned with professional indemnity insurance, to protect clients and users from negligent design (Hughes *et al*. 2006).

All of this advice and information are provided on the basis that there is no such thing as ‘perfect information’, and that designs are based on a prediction of the future. There are limits to rationality, and it is increasingly common for economists and organization theorists to acknowledge these limits. The concept of *bounded rationality* is well-established and appears to have been coined by Simon (1957). This refers to the idea that there are limits to what can be known about any situation. Thus, it is not possible, for example, to create a design that is complete in every detail before construction work commences on-site. Worse, the fact that construction occupies long periods of time means that designs and plans are essentially a prediction of the future, which is far from an exact science. Since we cannot have perfect information and cannot predict the future, it is inevitable that construction is based on incomplete and inadequate information, no matter how much resource and effort is invested during the design phase of a project.

Procurement is also a business process. Typically, buildings are significant in terms of a client’s expenditure, and they often dwarf the annual turnover of a contractor, designer, and client . This means that the risks associated with construction are very significant, and the businesses involved in the process will be keen to ensure that their exposure to risk is not so great as to threaten their survival. The complex and fragmented supply chains that come together in a project are all tied to the project by contracts of one form or another, creating a network of contracts. Every participating firm will have negotiated on scope, time, price, and the apportionment of risk. Because this is complicated, standard forms of contract have emerged over the years to play a significant role in setting up projects. While this helps to expedite the processes of project setup, it also often means that participants may not have considered in close detail, the impact of the precise risk apportionment for which they have signed up (Hughes and Greenwood 1996). Worse, standard forms are often amended so that what might appear to be a familiar contract may turn out to be unusual. These are some of the reasons why construction may appear to be an adversarial business that is beset with contractual disputes.

Many of the roles in construction are professional. What this means in practical terms is not straightforward and does not appear to be well understood within the industry. The idea of being ‘a professional’ is a mixture of dealing with complex client problems, the mobilization of explicit and tacit knowledge, exercise of judgement, social recognition, and the notion of placing the public good as a higher aim than mere client service (Evetts 2003).

The process used to acquire a project is said to be sustainable if the participants have ensured that all factors relating to the economic, social, and environmental needs and impact of the project have been duly taken into consideration (British Standards Institution 2010b).

Every construction project is different, and an appropriate organizational structure must be responsive to its context (Walker 2007). Thus, a certain amount of organizational design is required. Construction procurement is typically far more complex than other forms of procurement, for four reasons: (1) the purchase of construction occupies a considerable effort in preplanning; (2) it takes place over a protracted period; (3) single projects typically constitute a large proportion of suppliers' and buyers' annual turnover; and (4) construction involves fragmented, specialized supply chains involving a large number of separate companies.

The issue of sustainability raises some interesting questions for construction procurement. In addition to considering the somewhat simplistic opportunities for making sustainability a contractual clause within inter-firm relationships, there is also the question of whether more specialist skills are required in the process to deal with the issues implied by sustainable procurement.

## 19.3 Organizational Design

The process of organization involves splitting a complex task into interrelated parts. Organization theorists study all aspects of how people act within organizations. The focus here is on the key elements of why the structure of a project organization is particularly complex and difficult in the construction sector, as well as how the work may be managed and organized in order to increase the likelihood of achieving a sustainable outcome. But there is no 'silver bullet'. Just as Woodward (1965) once observed: there is "not one best way to organize": so there is no one best way to organize procurement for a sustainable outcome.

In order to organize complex tasks effectively, the interrelated parts have to be identified and understood. This requires understanding the structure of the industry, the structure of supply chains, and the structure of the professions. However, in order to introduce new societal agendas into the organization of complex tasks like construction, challenges to conventional practices are required. The friction is *institutional inertia*. By institutions, we mean not just the professional institutions and the institutions of government, but also routines, customs, and habits that are ingrained in everyday practice. Thus, it is not usually sufficient to simply agree that change must come about. Regulations, policy, and standards may have to be changed in order to influence practice. This is why it is interesting to focus on emerging policies and standards in the area of sustainable procurement. Even if everyone agreed that sustainability should be at the top of every agenda, institutional inertia needs a push.

Incidentally, there is one key issue in designing construction project organization structures that is not usually present in discussions of organization structure.

It comes about because of the specialization of tasks and the need to maintain continuity of work for specialized workers. As a result, multiple interdependent tasks in a project are generally carried out between specialist companies who are subcontractors, rather than within one large company. This means that the links between roles tend to be contractual, as well as organizational (Hughes and Murdoch 2001).

In addition to the complex, contractual interrelationships that produce a network of participants in the construction process, there are also professional identities and allegiances that influence how work is carried out. The presumption of professionalism is that society's agenda is more important than the client's. But even the professional agenda has limits in terms of authority and influence. Thus, the need for healthy and safe environments, for example, is legally enshrined in the UK within all aspects of construction project organization through the Health and Safety at Work Act (HSWA 1974), and specifically the Construction (Design and Management) Regulations. It is into this multilayered complexity that we seek to insert the sustainability agenda, which requires project teams to produce a built environment that is economically, socially, and ecologically sustainable (Brundtland 1987).

## 19.4 Sustainable Procurement

Sustainable procurement is one of the areas to have naturally emerged from the overall sustainable development agenda (Brundtland 1987). It is aimed at ensuring that the current use of resources does not compromise the ability of future generations to meet their own needs. As most organizational acquisitions are obtained by the process of procurement, and given the size of government procurement activities, procurement was identified as a primary means through which sustainable development can be achieved. Although the term "sustainable procurement" may sound very popular, it has a fairly recent history which is traced back to publications of the late 1990s.

Sustainable procurement is also known by terms such as "green procurement" and "responsible procurement". Like the wider agenda of "sustainability" to which sustainable procurement is linked, there is no generally accepted definition for the term. What is clear, however, is that it encourages taking environmental, economic, and social factors into account in decisions and processes around purchasing. In the last 2 years, major publications such as BS8903:2010 Sustainable Procurement (British Standards Institute 2010) and a CIRIA Guide to Sustainable Procurement (Berry and Mccarthy 2011) have been published to strengthen the business and ethical case for procurement which leads to more sustainable outcomes. Some of the current approaches for achieving this will now be examined.

Generally, sustainable procurement is classified into *product-based* and *supplier-based* (Wilkinson and Kirkup 2009). Sustainable procurement is *product*-based where an organization examines a product's movement along the supply chain and assesses the environmental credentials of themselves and of their suppliers. This path is commonly used when an organization wishes to understand the impact of a product or product range for strategic and marketing purposes. Such an approach can also provide a vivid picture of supplier processes. Sustainable procurement is *supplier-based* where an organization reviews the Corporate Social Responsibility (CSR) management systems of a supplier and whether its practices conform with law and to the CSR standards of the "buying" organization. Thus, the organization measures the environmental and social risks a supplier may impose upon it. When implemented effectively, this method will show whether a supplier meets the environmental standards of the buying organization, and if they are operating legally.

An examination of the 'serious' literature on sustainable procurement shows that most of it is published by government (particularly in the UK), suggesting it is either public-sector driven or politically important. The publications have also increased over the years, revealing growing interest in the area. BS 8903:2010 (British Standards Institute 2010) outlines a set of aims, values, and implementation and measurement procedures for sustainable procurement. CIRIA C695 (Berry and Mccarthy 2011), which is cross-referenced to BS8903, also reinforces the underlying principles of sustainable procurement and offers a seven-step approach for putting sustainable procurement into practice. Most other sustainable procurement publications are in the form of a "guide" or "report" intended to provide guidance and directions for practice.

In practical terms, examples of environmental issues to consider in sustainable construction procurement include the following:

### *19.4.1 environmental Issues*

- emissions to air (e.g., greenhouse gases, such as carbon dioxide and other pollutants);
- releases to water (e.g., chemical pollution of watercourses); releases to land (e.g., chemical fertilizers);
- use of raw materials and natural resources (e.g., sustainable forestry, biodiversity);
- use of energy (e.g., renewables);
- energy emitted (e.g., heat, radiation, vibration, noise);
- waste and by-products (e.g., recycling and waste prevention).

### *19.4.2 Social Issues*

- encouraging a diverse base of suppliers (e.g., minority or under-represented suppliers);
- promoting fair employment practices (e.g., fair wages, avoidance of bonded labor, workforce equality, and diversity);

- promoting workforce welfare (e.g., health and safety, trade union membership);
- enabling training opportunities and skills development (e.g., apprenticeships);
- community benefits (e.g., supporting community groups, volunteering);
- fair trade and ethical sourcing practices (e.g., fair pricing policies).

### *19.4.3 Economic Issues*

- job creation (e.g., green technologies, creating markets for recycled products);
- whole life costing;
- achieving value for money;
- supporting small and medium enterprises (SMEs) (e.g., facilitating opportunities for small businesses);
- reducing entry barriers (e.g., facilitating open competition);
- ensuring that operating business remains a viable operation, able to provide employment, and security;
- ensuring suppliers' agreements are at fair and viable margins.

Most parts of BS8903, and to some extent C695, are focused on the processes which enable organizations to achieve these aims. The fundamental measures relate to organizational policy and sustainable procurement policy and strategy. According to the guidance, generally, the procurement process ought to take sustainability considerations into account. The primary enablers include: leadership and governance structures, people, effective risk and opportunity management, engagement, and measurement of sustainable procurement.

In the UK, major government initiatives and reports have provided the fundamentals and enablers for driving sustainable procurement forward. 'Securing The Future' (DEFRA 2005) introduced five guiding principles and four agreed priorities for achieving sustainable development. 'Procuring the Future' (DEFRA 2006) provided the foundation for the UK's 'Sustainable Procurement National Action Plan'. These publications provided the framework for driving sustainable procurement forward in both public and private sector organizations, most of whom now have some kind of policy document on sustainable procurement. Most policy documents recognize that the main area to tackle in the near future is how to get people to make such practices part of their normal expectations and daily lives. This needs to happen before the objectives of sustainable procurement can be realized. For this to happen, effective decision making and organizational structures are required at all levels of public, corporate, and private life. There are many who think that it will not happen without some kind of formal governance intervention, whether through legislation or contracts. There is strong evidence that Swedish construction clients are setting out environmental requirements in their procurement documents, which sets up a condition that conforming bids have to meet the environmental requirements in their proposals (Sterner 2002).

The UK government has identified four principal means for achieving sustainable procurement in public construction infrastructure projects. They are:

(1) forward visibility of public investment in infrastructure; (2) new ways of assessing bids for work; (3) early contractor involvement in the bidding process; and (4) changes to regulatory timeframes. Through these means, the government expects to achieve significant savings in infrastructure costs.

Evidence from some empirical studies on sustainable procurement practices in organizations by Wilkinson and Kirkup (2009) and Sterner (2002) suggests that organizations are taking up the 'spirit' of sustainable procurement in their business practices. Thus, key advances have been made in defining, conceptualizing, measuring, and advancing the use of sustainable procurement practices in both public and private sector organizations. However, frameworks in the literature typically offer only a basic proposal for assessing and understanding the practicalities of sustainable procurement. Most reports assert the importance of the "triple bottom line" (environmental, economic, and social aspects) in accounting for their procurement practices. A comprehensive technique is needed for capturing the extent to which all three considerations are incorporated into any particular procurement process. However, policy guidelines cannot establish a process that suits all types of procurement in all industry sectors, thus the loose generality, which provides the framework within which specific strategies suited to each context, will need to be developed. While it is easy to say that a sensible balance between environmental, economic, and social priorities should be found, what that means in practice is an open question, perhaps amenable to research and probing in all walks of life.

In the public sector, DEFRA's Flexible Framework (DEFRA 2010) seems to be the accepted self-assessment mechanism for sustainable procurement. The Framework allows organizations to measure and monitor their progress on sustainable procurement practices over time. The framework was designed so that it could be used by all organizations regardless of their level of resources. It is a qualitative approach, which identifies five behavioural and operational themes that need to be delivered in each public sector organization, to deliver sustainable procurement: (1) people; (2) policy, strategy, and communications; (3) procurement process; (4) engaging suppliers and measurement; and (5) results. The five themes can be delivered by organizations at five progressive levels: foundation, embed, practice, enhance, and lead.

## 19.5 Sustainable Procurement in Practice

The report by Wilkinson and Kirkup (2009) on measurement of sustainable procurement in organizations takes a different approach. They present evidence of sustainable procurement policy and practices of the East Midlands Development Agency. Various methods that can be used for measuring the three various aspects of sustainable procurement are presented within the report. However, a number of techniques are structured around whole-life costing and carbon measurement techniques. Thus, the techniques presented are not techniques for measuring sustainable procurement, as such. And whole-life costing is not the simplest of techniques to apply. Detailed guidance on the application of whole-life costing to sustainable procurement can be found in the Standardized Method of Life Cycle Costing for Construction Procurement (British Standards Institution 2008).

Some large construction firms such as Skanska (2009) have had a well-developed organizational policy on sustainable procurement since 2009. The main areas covered under the policy include: supply chain and health and safety, ethical sourcing, equality diversity and inclusion, environmental and green sourcing, best value, and quality management. According to the Skanska policy document, "sustainable procurement is the value for money sourcing of products and services taking into account environmental, social, and technical aspects over the whole product or service lifecycle". The five principles outlined for achieving this are zero accidents, zero ethical breaches, zero environmental accidents, zero losses, and zero defects. The principles of sustainable procurement outlined in BS8903 are clearly wider than this and perhaps private sector organizations may be expected to do more to achieve many of the wider and more universal objectives of sustainable procurement, particularly in social and environmental aspects.

A UK-based institution that champions sustainable procurement practices is the Waste and Resources Action Programme (WRAP). This was established by the government to help the UK improve its recycling practices and has published its three-step guidance that organizations can apply to achieve sustainable procurement (Society of Local Authority Chief Executives and Senior Managers 2003). First: adopt a sustainable procurement policy; second, develop a dialog with suppliers; and third, check for sustainability through the procurement cycle.

These three examples illustrate the kind of approaches that are proliferating. It can be expected that every organization will develop such guidance and policies; those who do not risk falling foul of corporate social responsibility requirements. It is interesting that there are growing requirements that use various techniques of enforcement, policy setting, normalization, and economizing. Taking into account the whole-life costs of a facility, it is clearly in the long-term interests of any client of the construction sector to seek a sustainable solution because it will save money in the long run. But due to the sheer quantity of guidance documents, standards, and policies seems to indicate that it is not easy to persuade clients to spend less money. Perhaps this is explained by the simple fact that future money is cheaper than present money (because of net present value). Or perhaps there are perverse incentives that encourage profligacy. Clearly, more research is needed into the reasons for behavioral trends.

## 19.6 Conclusion

The sustainable procurement agenda is driving change in the approaches to business that are used in the construction industry. Significant changes are likely to occur in future, concerning specification of construction contracts, selection of suppliers, and mechanisms for awarding work. Government and public clients are making clear that they are seeking cost reduction through greater forward visibility of public investment in infrastructure (achieving more for less), and switching to whole-life outcomes rather than lowest cost bids; early contractor involvement in the bidding process and changes to regulatory timeframes. These are likely to translate into sustainable procurement policies and contract award mechanisms. However, spending money up-front in order to reap the benefits of savings in the future, and in order to reduce the adverse impact of climate change, seems to be strangely difficult to achieve, especially in public sector procurement. These are important research questions.

In theory, sustainable procurement seems a laudable and necessary concept. Appropriate incentives and organizational structures are required at all stages of the procurement cycle to help achieve it in reality.

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# Chapter 20
# The BRE Innovation Park: Some Lessons Learnt from the Demonstration Buildings

**Jaya Skandamoorthy and Chris Gaze**

**Abstract** The BRE Innovation Park features a number of demonstration buildings that have been built to the UK Government's Code for Sustainable Homes, which showcase the very latest innovative methods of construction, and cutting edge technology. This chapter explains the key features of these demonstration buildings, and provides some key lessons learnt from four of the demonstration homes on its performance in relation to the 'building fabric' and the 'energy strategy' for the building. *Learning Scope*: On successful completion of this chapter, readers will be able to (1) understand the different building innovations and technologies that are setting the benchmark for sustainability in the UK; (2) understand the government's Code for Sustainable Homes which is the new standard for all new build homes in the UK; and (3) learn some of the key lessons from the demonstration homes on their approach to the building fabric and energy strategy.

**Keywords** Innovation · Technology · Building · House · Standard · Code · Sustainability · Renewable · Energy · Water · Materials · Passive · Measurements · Refurbishment · Smart technology

## 20.1 Introduction

The BRE Innovation Park is a world leading and ground breaking demonstration development designed to give a glimpse of how the future delivery of sustainable buildings and communities can be achieved not only in the UK, but around the

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world. It features some of the world's most sustainable houses and buildings and over 300 different construction innovations and emerging technologies as well as a state-of-the-art community landscape designs. The buildings on the Park include the following:

- Hanson EcoHouse—constructed using traditional building materials, precisely assembled to conform to the best principles of innovative methods of construction;
- Renewable House—illustrates how renewable building materials, such as hemp, wood, and wool, provide excellent options for constructing low carbon, practical and affordable modern housing;
- Osborne House—shows that high quality, sustainable housing can be delivered affordably in volume;
- Barratt Green House—the first house on the Innovation Park to be built by a mainstream house builder, the Green House achieves Level 6 of the Code for Sustainable Homes;
- The Prince's House—demonstrates a simple, low-tech, and easy to build alternative for volume house builders seeking to meet increasingly stringent low carbon targets for new homes. (formerly known as The Natural House);
- Cub House—designed by property developer Charlie Greig and manufactured in the UK by Future Form, this ultra-modern and highly sustainable modular home is suitable for both social and private housing applications;
- Sigma Home—has been test run by a family to obtain a 'real' perspective on living in a home constructed for sustainability using the latest technologies;
- Victorian Terrace—the buildings have been transformed into three highly efficient terraced houses (the BASF Zone, the Saint Gobain Zone, and the British Gas Zone) which still retain the original character of the building;
- Willmott Dixon Healthcare Campus—points to a new age of healthcare that helps people to manage their conditions more independently by using both health clinics and their home.

The Park points the way toward the future, and the need for the UK to significantly reduce its $CO_2$ emissions if it has any chance of meeting the 2050 target of 80 % emissions reduction. It gives the construction industry the knowledge, and facilitates the radical change needed to meet this immense challenge by:

- giving developers, architects, and manufacturers the opportunity to try out a range of innovative designs, products, and materials before they are introduced in real communities;
- creating a new evidence base of knowledge about sustainable buildings that can be easily accessed by all;
- educating in a tangible way the key built environment stakeholders about sustainability and the different ways in which it can be achieved;
- being a catalyst for the creation of sustainable and desirable future communities.

Collectively, these buildings demonstrate diverse and innovative approaches and provide valuable lessons on how to achieve sustainable design and


**Fig. 20.1** Site of the BRE Innovation Park

construction. They share the common goal of having a low impact on the environment, but a high impact on the quality of life of building and community occupants and $CO_2$ emissions reduction.

## 20.2 The Demonstration Buildings

This section introduces the information of design and construction features of individual house relating the UK Code for Sustainable Home. Figure 20.1 shows the site of the BRE Innovation Park.

### *20.2.1 The Hanson House*

Built in 2007, the Hanson EcoHouse (see Fig. 20.2) was the first masonry house to achieve Code Level 4 under the Code for Sustainable Homes, with its construction bringing together the latest developments in off-site construction, thermal mass, and natural ventilation.

The House's recent refurbishment includes the application of the Structherm Insulated Render (IR) system, to demonstrate a retrofitted solution that delivers high degree of thermal efficiency, vapor permeability, impact resistance, and flexibility of color and texture.

Along with its distinctive appearance, provided by a steeply pitched roof and central chimney, the house's key features include:

- Thermal mass—2 years of tests on the house have demonstrated the benefits of high levels of thermal mass, which were achieved with pre-fabricated masonry external walls, heavyweight block internal partitions, and a pre-cast staircase and concrete floors. This mass allows the building to store heat during warm periods, and release it during cooler spells or at night. The tests proved the house's ability to stay cooler in summer and warmer for longer in winter;


**Fig. 20.2** Hanson EcoHouse (Code level 4)

- Natural ventilation—with a central stair core below the roof opening, the design maximizes convection in much the same way as a kiln (its shape being similar) draws hot air up through a brick stack and out of the chimney, while simultaneously drawing in cool fresh air at a low level. The kiln shape also creates a large, light filled open plan living area on the first floor of the building;
- Energy and water—a solar collector and ground source heat pump helps meet the house's energy needs. Sustainable Urban Drainage Systems (SUDS) compliant external paving allows rainwater to pass through it and into a tanked subbase. This combines with a layer of flexible piping linked to the ground source heat pump, to provide space heating and domestic hot water. The water is also filtered so that it is suitable for flushing toilets and watering plants.

### *20.2.2 The Renewable House*

Built in 2009, the Renewable House (see Fig. 20.3) was constructed with renewable and low carbon materials—including hemp, a commercial crop that absorbs $CO_2$ while growing. It is mixed with lime to produce the Hemcrete® used in the timber frame walls. In addition, Thermafleece™ insulation made from British sheep's wool keeps the carbon footprint down, and renewable materials in the paint and furnishings provide a comfortable environment.

Energy efficiency—careful attention to detail minimizes cold bridging and maximizes insulation. The timber and Hemcrete® structure, and FSC certified timber windows, delivers low U-values and good airtightness. The interior has new biorenewable carpet by DuPont made from corn and sugar.

**Fig. 20.3** Renewable House (Code level 4)


**Fig. 20.4** Osborne House (Code level 3)

## *20.2.3 The Osborne House*

The Osborne House (see Fig. 20.4) demonstrates that high quality, sustainable housing can be delivered affordably and in volume—and also flexibly, the house can be constructed in detached, semi or terraced versions, as well as in the form of flats up to three stories high.

The design is based on an adaptable combination of structural insulated panels, which create a structural shell that incorporates the internal leaf of external walls and party walls. In this house, the shell includes the first and second floors topped

**Fig. 20.5** Barratt Green House (Code level 6)

by a roof system that can contain a room in the roof space. The structure was erected and weather tight in one and a half days. Other key features include:

- Sustainable exteriors—Siberian larch has been used to clad the front of the house, with recycled plastic slates to the side, Eternit boarding to the rear, and a zinc finish to the roof. The pathways around the house have been made with permeable paving;
- Sustainable interiors—inside there is a heat recovery ventilation system, under floor heating using hot water circulation, electric skirting board heating, low use sanitary ware, and temperature control taps;
- Smart technology—is used throughout and includes a data delivery system showing energy consumption, live public transport information, and the ability to manage an on-site car club.

### *20.2.4 The Barratt Green House*

The Barratt Green House (see Fig. 20.5) was the first home on the Innovation Park to be built by a mainstream house builder. Aiming to achieve both outstanding environmental performance and wide public appeal, its design won the 2007 Home for the Future Design Award run by the Mail on Sunday, in which the winner was chosen by a public vote.

Built by Barratt Development PLC, key features of the Green House include:

- Code level 6—the house was designed (by architects Gaunt Francis) to meet both level 6 of the Code for Sustainable Homes and the Government's criteria for zero stamp duty;

**Fig. 20.6** Prince's House (Code 3–4)

- Future proofing—high levels of thermal mass in the structure will reduce the need for cooling during the hotter summers predicted to be a feature of climate change, and flexible internal spaces allow different layouts to suit changing family needs;
- Daylighting—high performance triple glazing and thermally broken wooden frames allow sufficient glazing to bring daylighting across the depth of the accommodation;
- Window shutters—the distinctive shutters are an attractive feature, but also optimize solar gain, control overheating, and prevent glare—and offer potential insulation benefits;
- MVHR—a whole-house mechanical ventilation system with heat recovery (MVHR) warms incoming fresh air using heat from air being exhausted from the building, and circulates it to the habitable rooms by a ductwork system;
- Research—The Green House is the subject of a rigorous, 2-year scientific testing program to assess every aspect of the design, construction, and materials.

### *20.2.5 The Prince's House*

The Prince's House (see Fig. 20.6) demonstrates a simple, low tech, and easy to build alternative for volume house builders seeking to meet increasingly stringent low carbon targets for new homes.

Built by The Prince's Foundation for Building Community, the Prince's House is a highly energy efficient structure that nonetheless reflects people's preference for traditionally designed buildings. It is constructed from natural materials including aerated clay block, lime-based renders and plasters, and insulation using compressed wood fiber and sheep's wool. The thermally coherent shell delivers energy efficiency and good indoor air quality, is simple and quick to build and is designed to appeal to an increasingly eco-aware homebuyer.

**Fig. 20.7** Cub house (Code level 5)

Key features of The Prince's House include:

- Natural materials—the solid walls of the house are made from strong, lightweight clay blocks that have high levels of thermal insulation, but lower embodied energy than conventional bricks. The walls are a single skin of aerated clay blocks with external lime render and internal wood fiber board providing good insulation. The roof tiles are clay and floors and windows made from FSC certified timber;
- Ease of manufacture—the simple construction can be realized with conventional skills but is quicker than traditional brick and block;
- Versatility and adaptability—the house can be constructed in a range of architectural forms including paired dwellings, squares, and terraces. It can be subdivided into configure a family home, maisonette, or smaller flat, reflecting changing demographics and people's needs over the long term;
- Health and wellbeing—the use of natural, nontoxic materials provides a healthy environment, promoting air movement without mechanical air conditioning. A research project is examining the impact of natural materials on air quality, on allergy resistance, and on general wellbeing.

## *20.2.6 The Cub House*

The ultra modern, highly sustainable, and factory-manufactured Cub house joined the BRE Innovation Park community in May 2010, after being launched to great acclaim at the Ideal Home Show (see Fig. 20.7).

The brainchild of property developer Charlie Greig, this modular home has been designed to Level 5 of the Code for Sustainable Homes and is suitable for both social and private housing. It is manufactured by the UK-based company Future Form, and designed to meet Lifetime Homes and Secured by Design standards. The house also has NHBC Building Control Type Approval, and the necessary accreditation for mortgage lenders and insurers.

The steel frame Cub house can be clad in timber, brick, or an innovative fiber glass cladding, and comes complete with fitted kitchen and bathroom in 51 $m^2$ modules. It competes on cost with traditional house building and demonstrates outstanding green credentials including:

- Recycled material—65–90 % of the primary material—steel—is recycled;
- Insulation—the walls are superinsulated to minimize heat loss;
- PV power—PV panels come with each home as standard. "Not only will running costs be low", says Charlie Greig, "but Cub owners can also generate an income from the energy they produce through the PVs";
- Heating—each Cub home is fitted with an exhaust air heat pump that ventilates the house as well as providing space heating and hot water;
- Water—rainwater harvesting and water saving devices are standard features;
- A rated—A/A + rated appliances and low energy lighting fixtures are used throughout.

### 20.2.7 The Sigma Home

The Sigma Home (see Fig. 20.8) is one of the country's first five star rated homes under the Code for Sustainable Homes. Presented as two semi-detached homes, one is fully finished and furnished as a three, but potentially a four bedroom four story townhouse to illustrate practically how such an innovative design can contribute to the contemporary lifestyle. The other is a 'blank canvas' to highlight the technology and the flexibility to produce different layouts. In this case a ground floor, one bedroom apartment/live-work unit with a three story, three bedroom triplex above. The Sigma Homes also benefit from a coordinated approach using Modern Methods of Construction (MMC), one of the most technologically advanced and sustainable forms of construction to satisfy the demands of Egan led methodologies and recent Government directives. The Sigma home embraces a hybrid approach to the application of different leading-edge off-site technologies. The smarter build process enabled the construction of two semi-detached four story structures in 8 weeks from the commencement to completion, compared to the traditional timescale of 24 weeks.

The Sigma Homes utilize renewable energy by way of heating hot water from solar thermal and photovoltaic roof panels, roof mounted wind turbines, and solar gain.

A solar stack and 'whole house' mechanical ventilation and heat recovery system controls temperature in a passive system. The stack sits centrally above the stairwell and sucks in warm air as it rises, in a similar way to that of a chimney. A heat sensor opens and closes a vent at the top of the stack to manage the optimum temperature in the building.

The high levels of insulation provided by the wall, floor, and roof elements are coupled with high performance timber windows to give excellent thermal performance of the external envelope. Add to this the airtight construction and

**Fig. 20.8** Sigma home (Code level 5)

detailing, ten times better than current Building Regulations requirements, the resulting design delivers energy performance 100 % better than Part L1A.

All timber and timber products are from managed sustainable sources.

All of the homes' internal, external, and security lighting (excluding the pod) is low energy and white goods are all A + or A rated. Water: an in-built Eco-play gray water recycling system reclaims shower and basin water for toilet flushing. All showers, taps, and washing machines have low water consumption.

### *20.2.8 The Kingspan Lighthouse*

The Kingspan Lighthouse (see Fig. 20.9) has achieved the requirements of Level 6 of the Code for Sustainable Homes by addressing aspects such as energy consumption/$CO_2$ emissions, water use, waste, pollution, and surface water runoff, the use of sustainable materials, health and well-being, management and ecology. The Kingspan Lighthouse is net-zero carbon—which means it has zero carbon energy supplies for space and water heating and all electrical power demand for the home, including electrical cooking and appliances. Around 30 % of the water in the house has been provided from rainwater harvesting or water recycling systems. This achieves the Code's requirement that not more that around 80 L of potable (drinkable) water should be consumed per person, per day.

Some of its key features of the Lighthouse are:

- Net-zero carbon (Code Level 6) home;
- All building materials and components used optimize the house's overall sustainability credentials;
- Reduced glazing—ratio of glazing to wall is 18 % as opposed to 25–30 % in a conventional house;
- High level of thermal efficiency and airtightness;

**Fig. 20.9** Kingspan lighthouse (Code level 6)

- Smart metering helping to monitor energy consumption to identify waste;
- 50 % reduced water costs compared to a conventional house;
- Mechanical ventilation with heat recovery (MVHR);
- Wind catcher providing secure night-time ventilation;
- Energy cost estimated at £31p/a;
- Minimal ground disturbance.

### *20.2.9 The Victorian Terrace*

As part of the rethinking housing refurbishment project, a disused Victorian stable block at the center of the BRE Watford site has been transformed into three energy efficient terraced homes fit for twenty-first century living (see Fig. 20.10).

Now a part of the BRE Innovation Park at Watford, visitors are able to learn about best practice refurbishment including the latest processes, materials, and technological advances.

The original stable block, built in 1855 alongside the country house Bucknalls at the center of our site, exhibited all of the problems associated with pre-1919 housing. It had solid (noncavity) brick walls, rattling single-glazed sash windows, a clay tile roof in poor condition, dampness, disrepair, and poor thermal performance—even resident bats (which under changed legislation now require special care and attention).

The design and renovation specification set tough performance targets whilst requiring the original character of the building to be retained. Low carbon materials and intelligent products were incorporated along with a digital communication infrastructure that monitors the condition and performance of the building and provides tele-assisted care for those needing it.

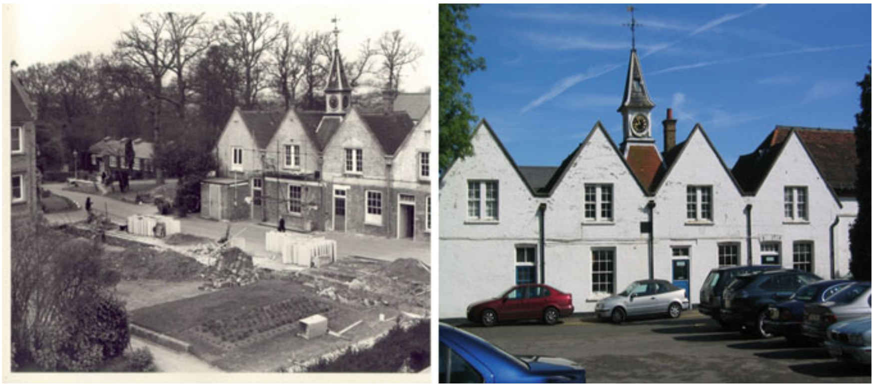

**Fig. 20.10** Victorian Terrace (before and after refurbishment)

The refurbishment energy target is

- SAP—minimum of 80;
- CO2—$\leq$35 kg/m$^2$/yr;
- Air permeability 7 m$^3$/h/m$^2$ at 50 pascals or below (current best practice is 5 m$^3$/h/m$^2$ at 50 Pascals or below);
- Energy saving—greater than 60 % improvement;
- Energy production (conventional)—high efficiency gas condensing boiler with state of the art zone controls;
- Energy production (renewables)—at least 10 % of energy demand.

To provide a convincing demonstration of what can be achieved through refurbishment, it is vital that improvements made to the design, structure, environmental conditions, and comfort levels of the Victorian Terrace are measured and documented. In addition to the mandatory investigations required for planning and legal compliance, BRE is undertaking a series of tests that will quantify the difference between pre- and post-refurbishment performance.

## *20.2.10 The Wilmott Dixon Healthcare Centre*

Originally, constructed as an exemplar school building, the flexibility of the Eurban structure was the key to allowing the alterations a safe and pain-free operation. The structure was not only able to cope with large structural modifications such as doors and windows, but also smaller alterations for services and esthetic purposes (see Fig. 20.11).

The design process was slightly unorthodox as there is no end-user/stakeholder, with the quality achieved through the experience of the team members and the sponsors involved with the project.

**Fig. 20.11** Wilmott Dixon healthcare centre (BREEAM excellent)

The Healthcare Centre features:

- A passively ventilated consulting room with electronically operated windows activated by temperature and $CO_2$ concentration sensors;
- Mechanical ventilation is provided to two treatment rooms via fabric ducts. Some of the fresh air is taken from the solar wall on the exterior of the building, which uses the sun's warmth to preheat the incoming air;
- Antimicrobial materials to reduce contamination risks;
- Transparent photovoltaic architectural glazing on the roof, by Polysolar, which delivers an estimated 3,000 kWh of electricity each year;
- An entrance ramp ('the Facility') which harvests kinetic energy produced by footfall to power other building systems;
- An IMI plug and play bedroom modular pod, which mimics natural light changes throughout the day supporting the human circadian rhythm and integrates cabinets and services in a retrofitted, flat pack solution;
- Other technology on display includes Breathing Buildings' e-stack technology, a low carbon natural ventilation system used at the UK's first BREEAM outstanding health facility in Sunderland, and i-Spy Digital's Care Messenger, which allows personalized messages to be sent to individual TV sets, overlaying commercial channels, and an important contribution to assisted living.

## 20.3 Lessons Learnt

Some of the key lessons learnt from the BRE Innovation Park were from four demonstration buildings that were built to the Government's Code for Sustainable Homes which was published in November 2006. These four demonstration homes were:

- Ecotech[1]—who built the Organics™ house, a Swedish timber frame two-story house on top of a one-story flat, both with air source heat pumps. Solar thermal panels and gray water recycling were supplied for both units. They were designed to Code Level 4;
- Hanson[2]—who built the Ecohouse™, an off-site produced masonry house, where the traditional mortar has been replaced with adhesive. It was built using a ground source heat pump, solar thermal panels, and rain water recycling. It was designed to Code Level 4;
- Stewart Milne[3]—who built Sigma™ house with a closed panel timber frame, photovoltaics, solar thermal panels, wind turbines, graywater recycling, and rainwater harvesting. It was designed to Code Level 5;
- Kingspan[4]—who built the Lighthouse™ using SIP panels with biomass boiler, solar thermal, photovoltaics, graywater recycling, and rainwater harvesting. It was designed to Code Level 6 and has received its post construction certificate.

From May 2008, all houses in England were assessed against the Code (or issued a statement of nonassessment). In 2010, all new homes in England had to achieve the Code's energy use as laid out for level 3. This then changes to level 4 in 2013 and level 6 in 2016.

## *20.3.1 The Building Fabric*

### 20.3.1.1 Building Strategy

One of the biggest changes introduced by the Code is the way in which the building fabric is constructed for insulation, thermal bridging, and airtightness. Up to code level 4, there are two basic forms of strategy that can be adopted. The first as used by Ecotech was to concentrate foremost on the building fabric, particularly airtightness. The alternative which was used by Hanson was to build a good fabric, but to use renewables, such as ground source heat pumps to obtain the Code level.

For those seeking Code level 5 and above, both approaches are necessary.

The performance of the building fabrics is shown in Table 20.1.

[1] www.eco-techgroup.com/

[2] www.hanson.co.uk/713/buildingsystemsandmmc/hansonecohouse.html

[3] www.stewartmilne.com

[4] www.kingspanoffsite.com/kingspan/case_study/market/housing?case=lighthouse

**Table 20.1** Building fabric performance

| | Units | Ecotech | | Hanson | Stewart Milne | Kingspan |
|---|---|---|---|---|---|---|
| | | Flat | House | | | |
| *U values* | | | | | | |
| Doors | $W/m^2$ K | 1.00 | 1.00 | 1.30 | 2.00 | 0.31 |
| Windows | $W/m^2$ K | 1.30 | 1.30 | 0.80 | 0.68 | 0.68 |
| Roof windows | $W/m^2$ K | | | 1.70 | | 1.40 |
| Ground floor | $W/m^2$ K | 0.11 | | 0.16 | 0.13 | 0.11 |
| Majority of walls 1 | $W/m^2$ K | 0.17 | 0.17 | 0.19 | 0.15 | 0.11 |
| Other wall areas | $W/m^2$ K | | | 0.12 | | |
| Main roof area 1 | $W/m^2$ K | N/A | 0.06 | 0.12 | 0.13 | 0.11 |
| Other roof areas | $W/m^2$ K | | | 0.19–0.21 | 0.11 | 0.05 |
| *Heat loss* | | | | | | |
| Fabric | W/K | 59.86 | 45.81 | 75.19 | 60.96 | 55.62 |
| Thermal bridges | W/K | 10.34 | 8.26 | 24.70 | 19.93 | 12.17 |
| *Airtightness* | | | | | | |
| Designed | $m^3/m^2$ h | 1.00 | 1.00 | 5.00 | 1.00 | 1.00 |
| Achieved | $m^3/m^2$ h | 2.77 | 2.77 | 4.83 | | 1.27 |
| *Heat loss parameter* | | | | | | |
| Designed | $W/m^2$ K | 0.70 | 0.78 | 1.28 | 0.90 | 0.80 |
| Achieved | $W/m^2$ K | | | | | 0.80 |

#### 20.3.1.2 Insulation of the Build Elements

As can be seen from the table, the build elements used in the houses were of a very high specification.

The walls were either closed panel timber frame, SIPs (Structurally Insulated Panels), or cavity insulated masonry. In the case of the SIPs, the excellent 0.11 U value was obtained by using two layers of the SIP panels instead of the normal one.

The excellent roof U value of the Ecotech roof was through an off-site constructed roof containing a combination of rigid and mineral wool insulation developed with Corus[5].

All the doors and windows (except for the roof lights) came from Scandinavia (Elitfonster[6]—Ecotech, Nordan[7]—Kingsapan and Stewart Milne, and Swedish Timber Products[8]—Hanson). The roof lights were supplied by Velux[9] in the case of Kingspan and The Roof Light Company[10] in the case of Hanson. In the case of

5 www.corus-hipoint.com/

6 www.elitfonster.se/

7 www.nordan.co.uk/

8 www.swedishtimberproducts.co.uk/

9 www.velux.co.uk/

10 www.therooflightcompany.co.uk/

Ecotech, the windows were pre-installed in the factory in Sweden that made the wall panels. All these products give excellent performance, as can be seen in Fig. 1, and come from sustainable sources.

The Code gives credits for houses that conform to "Secure by Design—Sect. 20.2"[11], which specifies windows and doors. These are relatively easy credits to obtain and "Secured by Design" compliance should be specified up front. The Ecotech, Kingspan, and Stewart Milne houses all achieved the credits for "Secure by Design" conformance.

There is a potential design conflict between obtaining the credits for Lifetime Homes compliance (flexible and adaptable homes for people with disabilities)[12], good daylighting, and the desire to have a well-insulated fabric.

Lifetime homes that require windows should be not more than 800 mm from the floor, whereas the credits for daylighting are awarded for amount of daylight and views of the sky. Both of these tend to drive up window sizes, whereas for insulation purposes the house is better if windows are smaller.

This conflict came to light with the Kingspan house which was originally designed to have two roof lights. One of these had to be removed bring up the performance of the fabric. However, Kingspan was still able to obtain all the daylighting and Lifetime Homes credits.

The Hanson house also obtained the daylighting credits. Both the Kingspan and Hanson designs were helped by the use of roof lights placed directly over the kitchen, where the requirement for daylight is at its greatest. In the Stewart Milne house a view of the sky was not obtainable, and the kitchen did not have "sufficient" daylight, and they therefore received one out of a possible three credits.

#### 20.3.1.3 Thermal Bridging

The minimization of thermal bridging is naturally of critical performance to the success of these dwellings. The main causation of thermal bridging occurs at the junctions between the panels, through and around window and door frames and piercings through the fabric e.g., balconies.

Ecotech had a very successful freestanding balcony that overcame the problem of cantilevering of the main fabric of the builder and some of the windows and doors e.g., those produced by Nordan have insulation within the timber window frame that acts as a thermal break.

The junctions of wall panels to floor slab and wall panels to roof are particularly susceptible to thermal bridging. The ground floor insulation detail on the Ecotech house illustrates a solution to thermal bridging. After the sole plate was laid, the inside of the plate was topped up with rigid insulation and then the external walls were fixed down onto the sole plate around the outside of this insulation.

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11 www.securedbydesign.com/

12 www.lifetimehomes.org.uk/
www.bre.co.uk/innovationpark

At the roof level, the traditional eaves design can have minimal insulation at the point where the roof structure meets the wall plate. The designs on the Innovation Park tend to "wrap" the insulation round this point as can be seen in Fig. 2 concept sketch, which is based on a detail used by Ecotech.

#### 20.3.1.4 Airtightness

Achieving good airtightness is one of the most challenging parts of the Code.

Two strategies were adopted for making the dwellings airtight. Stewart Milne adopted a floor by floor approach, whereas the others adopted a whole-house approach. The floor-by-floor approach led to difficulties sealing around down lighters as well as around the back of the bathroom pods. This led to air being able to escape to the outside through the floor cassette zone. The whole-house route appears therefore to be simpler and more robust.

Having said that airtightness is still challenging. Houses with large air volumes in proportion to their footprint such as the Hanson house and/or have complex build constructions e.g., the curves on the Kingspan house have more difficulty achieving very low airtightness values, e.g., 1 $m^3/m^2$ h, and more difficulty in doing remedial work afterwards. Simpler designs with relatively low ceilings and straight walls and floors, such as the Ecotech house, are easier.

In addition, Ecotech limited the number of holes in the external walls and the gaps around openings:

- On the inside there are no plugs or sockets—they are all on the internal walls;
- On the outside, the freestanding balconies avoid joists sailing piercing the external walls to form the balcony floor;
- When the windows and doors are fitted in the factory, the walls are made up around them to limit gaps between the window/door frame and the hole in the panel.

The gaps between panels and plates tended to be filled with extruded sealants in the form of jells or foams. One notable exception to this was Ecotech that relied upon two rubberized gaskets prefitted to the panels. However, no sealant was applied to the underside of the sole plate and on reflection it should have been. Gaskets and to a lesser extent tapes would appear to be preferable solutions for sealing these very airtight buildings than liquid or foaming sealants, since they give off less volatile organic compounds, which in turn will require good ventilation to remove from the indoor air. Reducing the number of joints, through the use of large panel systems will undoubtedly help.

With the exception of Ecotech, Kingspan, and Stewart Milne did not hit their lowest hoped for airtightness levels (1 $m^3/m^2$ h). Even after remedial work, Kingspan and Stewart Milne still did not achieve their goal. Although Kingspan was close at 1.27 $m^3/m^2$ h. Hanson was more conservative about what they hoped for; 5 $m^3/m^2$ h and achieved it first time.

#### 20.3.1.5 Key Lessons Learnt

In summary, the lessons learnt with regard to fabric of these buildings:

- Keep the openings in the house to a minimum. If it is desired to pick up credits for Lifetime Homes and daylight provision as specified in the Code, then let this be used to specify the minimum;
- Low U value sustainably sourced timber windows and doors that are also Secure by Design approved do exist. For these projects they were all sourced from outside the UK. However, the UK fenestration suppliers are catching up;
- Pay special attention to cold bridging especially between the ground floor wall and floor and around the eaves. For high performance applications consider using window and door frames with a thermal break;
- When first approaching airtight home design assumes the worst at the planning stage e.g., 5 $m^3/m^2$ h;
- Aim to make the whole-house airtight including the floors within the airtight zone;
- Simple houses with straight walls and low ceilings are easier to make airtight.
- Large panels have fewer joints;
- Joints should be gasketed or taped rather than relying on jell or foam sealants;
- Remedial work for airtightness is difficult, particularly in houses with complex internal geometry or inaccessible ceiling areas.

### *20.3.2 Energy Sources, Overheating, and Ventilation*

#### 20.3.2.1 Building Strategy

This section is mainly concerned how the different companies on the Innovation Park made choices over energy sources, minimizing the potential for overheating, ventilation, and some of the associated issues that arose.

Hanson's strategy was, in contrast, to that taken from the other three. The performance of the fabric for insulation and airtightness, whilst very good, was more modest than that of the other houses. Their way of achieving low energy performance was more reliant on low/zero carbon (LZC) energy sources. At the same time, the fabric of the house has high thermal mass through the use of masonry and precast concrete and this influences the ways in which it is heated, cooled, and ventilated.

The fabric of the other houses is all relatively low thermal mass. This means that they relatively quickly respond to changes in temperature, both inside and outside, and therefore need heating, shading, and ventilation strategies to match.

**Table 20.2** Sources of energy

| | Ecotech | Hanson | Stewart Milne | Kingspan |
|---|---|---|---|---|
| Gas boiler | | | √ | |
| Biomass boiler | | | | √ |
| Ground source heat pump | | √ | | |
| Air source heat pump | √ | | | |
| Solar thermal panels | √ | √ | √ | √ |
| Photovoltaic panels | | | √ | √ |
| Wind turbine | | | √ | |

#### 20.3.2.2 Sources of Energy

Table 20.2 shows the different types of energy sources adopted in the different houses:

The use of LZC technologies such as these can contribute toward credits within the code in two areas, through:

- reducing the Dwelling Emission Rate (DER)—Ene1; *and*
- for the percentage reduction in DER that has resulted from their installation—Ene7.

Ene7 gives up to a maximum of two credits for a 15 % reduction in carbon emissions and all four houses achieved maximum credits.

##### Generating Electricity

Microgeneration was adopted for electricity generation by Stewart Milne and Kingspan as being the only way to achieve Code levels 5 and 6. Both adopted photovoltaic panels, but Stewart Milne decided to use wind turbines as well.

Photovoltaics are expensive, but effective. For the amount of electricity required for Code levels 5 and 6, they require a large amount of roof or wall area for mounting and this in turn affects the architecture of the house. In the case of the Kingspan house there are 47 $m^2$ of photovoltaic panels, which led to a need to increase the roof area in order to fit them on.

One issue that designers must be aware of when using photovoltaic's is that SAP uses the kilowatt peak (kWp) value of panels and not the higher kilowatt hour (kWh) that can also be found in the manufacturer's literature.

Stewart Milne trialed a wind turbines on their house. These were designed for turbulent wind flow, but the BRE site, along with most suburban locations experiences less than one half of the wind speeds assumed in the manufacturer's literature. The relationship between wind speed and power output is that power is in proportion to the cube of the wind speed. This means that if wind speed is half of that assumed than the power produced will be quartered. As it turns out the wind turbines on the Stewart Milne house have produced one-tenth of the power that had been hoped for, and in order to compensate an extra 0.8 kWp of photovoltaic panels had to be mounted onto the wall of the house.

Micro wind can work well in locations that are more exposed.

### Low Energy Lighting and SAP

With at least one of the houses on the Innovation Park, initial SAP assessments were submitted with low energy lighting being shown in 100 % of locations. The maximum allowed within the SAP methodology is 30 %. Houses designed with greater percentages of low energy lighting do not gain extra Code credits for reducing carbon dioxide emissions. The April 2008 version of the Code Technical Guidance will allow for the first time all low energy lighting in Code Level 6 houses to be included in the SAP calculation.

Separate additional credits can be obtained for the provision of internal and external *fixed dedicated energy efficient lighting fittings,* and these are not affected by the 30 % ceiling in the SAP calculations.

### Heating and Hot Water

The Hanson house uses a ground source heat pump to provide underfloor heating. Ground source heat pumps are designed to minimize the amount of pipework in the ground and this limits there power output. They therefore work best when they can just "tick-over" and not having to adjust in wildly changing demand. Buildings using heat pumps with underfloor heating should be well insulated and if they have a high thermal mass fabric, like the Hanson house then this is a bonus. Since high thermal mass buildings are by the nature slow to change temperature. They perform well with a heating system that is just "ticking over" most of the time. The heat pump is supplemented by the solar thermal panels for hot water, which are cost-effective source of renewable energy.

A feature of the Hanson solution is that the pipe work for the heat pump is placed under the permeable paving slabs, and therefore is installed at the same time as the paving is laid. The overall system is simple and reliable.

The Ecotech house has relatively low thermal mass due to its timber frame construction. Ecotech has installed warm air heating using an air source heat pump supplied in their Viessmann *compact service unit*. By heating the air, the temperature of the inside of the dwelling quickly responds. This would not work so well in a high thermal mass building, where the fabric would take some time to absorb heat from the air until it had reached a temperature equilibrium.

Supplemented with the solar thermal panels, the heat pump also provides hot water.

The use of the Viessmann *compact service unit* is an effective code compliance solution because it combines a heat pump, with a ventilation system and a hot water tank as one system. Most of the information required for assessing the heating of the dwelling against the Code could be found within Viessmann technical documentation.

The Stewart Mine house adopted a heating and hot water solution that will appeal to many developers. Conventional underfloor heating is provided using a gas boiler. The 14 kW boiler, the smallest that Stewart Milne could source, is oversized for the 4 kW potential demand. Hot water is supplemented from solar thermal panels.

Radiators would have been preferable to underfloor heating in that they can react more quickly. Underfloor heating systems, when you include the floor structure, give a heating system with relatively high thermal mass. The temperature of the rest of the low thermal mass fabric could potentially change relatively quickly, but the heating system will have a delay built into it before it can react accordingly.

Having said this, the Stewart Milne house still shows that it is possible to design Code Level 5 houses using systems that will be largely familiar to the existing contractor base and with known reliability in the field.

The Kingspan house used a biomass boiler because of its use of renewable wood pellets; this provides warm air space heating and hot water. The hot water is supplemented from the solar thermal panels on the roof.

Biomass boilers are a good solution for communal heating systems but are currently oversized for one off dwellings.

### Overheating

The sources of overheating come from the external environment or internal loads such as from cooking, washing, electrical goods, heating, hot water systems, and the body heat of occupants. These internal loads have been minimized in the houses on the Innovation Park through the use of low energy electrical goods, low energy lighting, and well-insulated hot water systems.

Overheating can be counteracted in low energy buildings through a combination of good ventilation, shading, and thermal mass. The key aim is to make sure that occupants do not feel a need to install air conditioning.

All the houses used shading to some extent. The Ecotech house used balconies, the Stewart Milne house used canopies, and the Kingspan house used external shutters. External shutters are effective at all sun angles; low in autumn and spring and high in the summer.

Thermal mass works well for keeping buildings cool provided there is sufficient ventilation over night to let the fabric of the building release the energy that has built up during the day. If this does not occur, then it is possible in extended hot weather for the building to become increasingly hot as each new day dawns.

The Hanson house illustrates the effective use of the combination of high thermal mass, good ventilation, large window vents, and a passive stack. Throughout the summer of 2007, which admittedly did not have many extremely hot days, feedback suggested that the Hanson house remained comfortable.

Thermal mass is at its most effective if the mass is located on the inner surfaces of the building. In the case of the Hanson house:

- the block work internal walls are all skimmed, as opposed to plasterboard on dabs which puts an air gap behind the plasterboard isolating it from the block work behind; and
- the concrete stairs and floors have been tiled rather than carpeted.

For the other houses on the park, the relatively lower thermal mass of their main structure (timber frame and SIPs) resulted in some alternative strategies being adopted.

Kingspan have supplemented the low thermal mass of their SIP panels by the use of concrete panels attached to the ground floor of their house and with tiled floors inside. Tiles and slates can be a very effective means of adding thermal mass.

Kingspan and Stewart Milne have experimented with the use of *phase-change materials*, Micronel from BASF (see Footnote 1) and Energain from Dupont (see Footnote 1), respectively. These systems use a wax that typically melts at around 26 °C as a form of latent heat storage that absorbs heat out of the building as it starts to overheat. This is an interesting development, worthy of further research. Unfortunately, the wax is flammable and therefore the product needs to be insulated from fire behind plasterboard. This has raised questions about its effectiveness in the Innovation Park house applications. Stewart Milne is continuing to assess the effectiveness of phase-change materials in their house.

Of all the rooms in a dwelling that need to be at a comfortable temperature, the bedrooms are the most important. The Hanson and Kingspan houses addressed this by placing the bedrooms on the ground floor. In hot weather, the rooms are cooler through having contact with the ground and because any heat in the dwelling heat tends to rise to the upper floors. The situation is improved further by having north facing bedrooms, so avoiding solar gain.

#### 20.3.2.3 Ventilation

For houses with high-performing fabrics such as those on the Innovation Park, appropriate ventilation strategies are an important consideration. Ventilation systems can be passive or mechanical (with or without heat recovery). Code level 5 and 6 houses will almost certainly require heat recovery. Ecotech Kingspan and Stewart Milne have adopted mechanical ventilation with heat recovery (MVHR) systems in their houses.

The Hanson house uses passive ventilation to keep the house cool in hot weather. This can work well where hot air can be vented through the lantern, and there are good sources of cooler incoming air such as through open louvered and meshed ventilation panels at the side of the windows (see Footnote 1).

The Kingspan and Stewart Milne houses also have lanterns which can be used as a means of dumping warm air in the summer. The downside of lanterns is that they are a cause of heat loss in cold weather.

All the lanterns on Innovation Park experienced installation difficulties that ranged from installers forgetting to insulate them, being damaged on site or the hole in the roof not being the correct size. Care will need to be taken when specifying, designing, or installing lanterns.

Where MVHR systems have been used, a number of other problems were experienced. The first area to consider at the design stage is whether the MVHR systems appear in Appendix Q of SAP. This means that they have been assessed and have a recognized efficiency that is likely to be better than the default efficiencies otherwise allowed within SAP.

Installation can also be difficult. It is vital that the duct work installed is exactly to the specification laid out in the design and follows the installation checklist that is available on the SAP appendix Q website (see Footnote 1). Areas to watch out for are the use of flexible ducts where rigid duct was specified, longer pipe runs than specified, more bends than specified, and a lack of insulation around ductwork. All these things can have a significant impact on the efficiency of the system and often arise through pressure on space in floor and service zones through design failure or through lack of consideration by other trades.

A way of increasing confidence in the conformance of the build to specification is to bring the systems in prefabricated. This was the route taken by Ecotech and is something that Stewart Milne will be working on in the future. In the Ecotech house, the Viessmann compact service unit contains most of the MVHR system. The bulk of the rest of the ductwork was installed in the factory that produced the kitchen/bathroom pod. This made for a simple and effective installation on site.

#### 20.3.2.4 Skills

All the houses on the Innovation Park showed the need to address skills shortages in the industry. Design, site supervision, and sales will all need to develop new skills to deliver these energy efficient dwellings to end-users. Designers need to understand what to specify and which design combinations work best. Site supervisors will need to become project managers. And sales representatives will need to be able to make a much more technical sale and to be able to explain to buyers how to use their new home.

For those who built the homes, there is a need to understand the importance to building to specification, particularly, when it comes to airtightness and ventilation systems. There is also a shortage of people who understand LZC carbon technologies and in particular how to connect them—a problem identified by Hanson in integrating the solar water panels to ground source heat pump. These issues would be eased through a greater use of prefabrication.

#### 20.3.2.5 Key Lessons Learned

- Photovoltaic's are likely to be the most appropriate method of microgenerating electricity on most sites;
- Microwind turbines are ineffective in many suburban and urban locations;
- SAP calculation can only allow for a maximum of 30 % low energy lighting, except in the case of Code Level 6 houses;
- Most boilers are oversized for the heating demands in low energy dwellings, although this will not normally affect their efficiency;
- Gas boilers can be used in designs for Code level 1–5 houses;
- Solar thermal is a relatively cost-effective and therefore popular source of renewable energy;
- Current biomass boilers are best used for communal heating when used with new dwellings;
- Appropriate ventilation, shading, and thermal mass will minimize overheating.
- Shading can be improved through external shutters, balconies, and canopies;
- Consider placing bedrooms downstairs to keep them cooler;
- Thermal mass can be increased through the use of additional heavy weight panels, tiles, and plaster skim onto blockwork;
- Specify and install lanterns with care;
- The use of louvered and meshed ventilation panels in windows increases natural ventilation whilst maintaining security;
- Consider using the most efficient MVHR systems listed in Appendix Q of SAP, and install them in accordance with the installation checklist on the SAP Appendix Q website;
- Allow for enough space in floor and wall zones for MVHR ducting and take account of this when designing the storey heights of the dwelling;
- Consider prefabricating MVHR systems and their ductwork off site in order to make conformance to specification more likely;
- Site managers need to become project managers;
- Designers need to be technology integrators;
- Sales representatives will require a technical understanding;
- Develop contractors who have knowledge of airtightness and renewables, and where appropriate have a fully integrated installation and commissioning package.

## Further Sources of Information

Complying with the Code for Sustainable Homes Lessons learnt on the BRE Innovation Park, November 2009

Improving Airtightness in Dwellings, Energy Saving Trust (http://www.energysavingtrust.org.uk/housingbuildings/publications/), November 1997—Revised October 2005

Energy Efficiency and the Code for Sustainable Homes—Level 3, Energy Saving Trust, January 2008

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Renewable energy Fact Sheet 8, Biomass Small Scale, Energy Saving Trust, November 2005

Domestic Ground Source Heat Pumps: Design and Installation of Closed Loop Systems—A Guide to Specifiers, their Advisors and Potential Users (CE82), Energy Saving Trust, June 2007

Solar Water Heating—Guidance for Professionals, conventional indirect models (CE131), Energy Saving Trust, March 2006

Reducing Overheating a Designer's Guide (CE129), Energy Savings Trust, March 2005

Energy Efficient Ventilation in Dwellings—a Guide for Specifiers (GPG268), Energy Savings Trust, June 1999, Revised March 2006

Photovoltaics in Buildings—Guide to the Installation of PV Systems 2nd Edition, DTI Publication, 2006

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