Computational Support for the Selection of Energy Saving Building Components

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Computational Support for the Selection of Energy Saving Building Components

Proefschrift

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Summary

Computational Support for the
Selection of Energy Saving Building Components

Pieter de Wilde
PhD-thesis, Delft University of Technology, 2004

Buildings use energy for heating, cooling and lighting, contributing to the problems of exhaustion of fossil fuel supplies and environmental pollution. In order to make buildings more energy-efficient an extensive set of 'energy saving building components' has been developed that contributes to minimizing the energy need of buildings, that helps buildings to access renewable energy sources, and that helps buildings to utilize fossil fuels as efficiently as possible. Examples of such energy saving building components are heat pumps, sunspaces, advanced glazing systems, thermal insulation layers, etc.

Building simulation tools appear to be a suitable instrument to support decisions regarding the selection and integration of energy saving building components: they can provide detailed information on the thermal performance of buildings that have not yet been built, thereby allowing objective comparison of different design options under identical conditions. However, in general the actual use of simulation tools to provide information to support the selection of energy saving building components does not live up to this expectation. The development of new building energy simulation tools shows a continuous increase of capabilities and complexity. This trend increases the dependency on adequate modeling and expertise, and thereby increases the barriers to integration of building design process and building simulation even further.

Therefore, the central goal of the PhD-project is the *development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components*. The strategy is to be substantiated by development of a prototype that demonstrates the feasibility of the strategy.

The work presented in this thesis consists of four main research activities, all focusing on the use of simulation tools to support the selection and implementation of energy saving building components: 1) analysis of the design process of current energy-efficient building projects; 2) development of an approach for well-founded selection of these components; 3) analysis of the suitability of existing tools to support the selection process, and development of ideas for improvement of these tools; 4) development of a strategy as well as a proof-of-concept prototype that provides support for the selection of energy saving components and that demonstrates the viability of the proposed changes.

Analysis of current energy-efficient building projects
The analysis of current energy-efficient building projects was initiated by a lack on unbiased information on the way in which energy saving building components are selected in current practice, and lack on information of the role of simulation tools in this selection process. The goal of the analysis was to find out for recent prestigious building design projects in the Netherlands how this selection took place, and what role tools played in supporting the selection.

In order to attain this goal three case-studies and a survey were conducted. The case-studies provided in-depth information on three projects; the survey demonstrated the representative ness of the findings from the case-studies for a larger sample of energy-efficient buildings.
The overall findings are that in current projects simulation tools do not play an important role in the selection of energy saving building components, since these tools are used in later phases than those relevant for the selection, and are only used for different purposes (optimization and verification rather than to support choices). Instead, most energy saving building components are selected based on analogy: use of similar components in previous buildings by the architect or consultant, or the use of these components in demonstration projects. It appears that decision-making on energy saving building components is based on simple, heuristic decision rules. Yet it seems preferable to apply multi-criteria decision rules to the selection of these components, ensuring that different requirements are considered in the decision-making process. Hence there is a need to improve both the selection procedure as well as the tools that support that selection.

An approach for well-founded selection of energy saving building components
The development of an approach for well-founded selection of energy saving building components had as goal to improve the current way of selecting these components. Requirements and constraints for making well-founded choices have been identified and used to assess existing theories for making design decisions. An approach for performance-based selection of energy saving building components has then been developed, using applicable elements from existing theories to define the essential steps: definition of an option space, identification of relevant functions, specification of performance indicators, prediction of performance for all options and all performance indicators, and evaluation followed by selection of the most desirable option.
This approach rationalizes the selection procedure, and makes the role of subjective assessment explicit. Since it is based on performance prediction, it provides an optimal base for the use of simulation tools. The viability of this approach has been demonstrated through application of the approach to an example.

Analysis and improvement of tools
Once the selection procedure had been developed, the next goal was to improve the tools that support this procedure. The analysis and improvement of tools for the selection of energy saving building components consisted of the following steps: analysis of the different main categories of tools (design tools, modeling tools, analysis tools, support environments and others) and their role in supporting the selection of energy saving building components, and assessment of existing tools as well as identification of possibilities for improvement of the two most important categories (analysis tools and support environments).
It was found that existing analysis tools are capable of supporting the selection according to the performance-based approach, on condition that enough time and expertise is available for the modeling and simulation work. Support environments are mostly still under development and have not yet gained widespread use.
Analysis tools can be improved through reverse-engineering, which clarifies the building design alternatives and performance indicators that can be handled by these tools. Support environments can be improved by embedding analysis tools as well as a selection mechanism that helps users to find a suitable (analysis) tool for any specific (analysis) job.

A strategy and prototype for the selection of energy saving components
The final goal of the research project was the development of the strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, and the realization of a substantiating prototype that shows the viability of this strategy. In order to reach this goal the afore-mentioned ideas on improvement of the process and support tools have been combined. Participation in an international research project, the Design Analysis Interface (DAI) - Initiative, provided the final elements needed for completion of the research.

A strategy for selection of energy saving building components has been developed in this thesis that consists of the following elements:

1. Energy saving building components should be selected according to a procedure that consists of definition of an option space, identification of relevant functions, specification of performance indicators, prediction of performance for all options and all performance indicators, evaluation of predicted performance and selection of the most desirable option.
2. Availability of time and expertise for modeling and simulation work are the most important limiting factors that hinder the application of existing building performance simulation tools in support of the selection of energy saving building components. In order to overcome this problem the analysis request must be stated unambiguously. At the same time, building performance simulation tools must be pre-conditioned (reverse-engineered) in order to meet these specific analysis requests.
3. The procedure for the selection of energy saving building components must be assisted by the use of a support environment that provides a mechanism that gives users access to different (embedded) building performance simulation tools for doing specific analysis tasks.

A prototype of a Design Analysis Interface (DAI) - Workbench has been developed that demonstrates the feasibility of better integration of building analysis tools and building design process through the use of a layered, process-centric approach, thereby showing the viability of the ideas to provide improved computational support for the selection of energy saving building components. The concept of analysis functions links the analysis process with simulation tools by matching analysis task and tool capabilities. An analysis function gives an exact specification of the performance indicator that is to be generated by the analysis.
Of course, full computational support for the selection of energy saving building components can only be achieved once the DAI-Workbench contains a set of analysis functions that covers most relevant performance aspects for buildings with such components, plus qualifying tools and interfaces from analysis functions to those tools.

Future work on the integration of building simulation and building design requires further development of support environments that capture and support the analysis process itself, and that provide access to tools that are able to support relevant process steps. Reverse-engineering of simulation tools to match specific analysis tasks seems an important task in order to increase the applicability of these tools.

Samenvatting

Rekenkundige Ondersteuning voor de
Selectie van Energiebesparende Gebouwcomponenten

Pieter de Wilde
Proefschrift, Technische Universiteit Delft, 2004

Gebouwen gebruiken energie voor verwarming, koeling en verlichting en dragen daarmee bij aan de uitputting van de voorraad fossiele brandstoffen en aan de vervuiling van het milieu. Om gebouwen efficiënter met energie om te laten gaan is er een uitgebreide set van ‘energiebesparende gebouwcomponenten’ ontwikkeld die bijdragen aan het minimaliseren van de energiebehoefte van gebouwen, die gebouwen in staat stellen duurzame energiebronnen te benutten, en die meehelpen eventueel toch nog benodigde fossiele brandstof zo efficiënt mogelijk te gebruiken. Voorbeelden van dergelijke energiebesparende gebouwcomponenten zijn bijvoorbeeld warmtepompen, serres, geavanceerde raamsystemen, en thermische isolatie.

Gebouwsimulatie programma’s lijken een bij uitstek geschikt hulpmiddel om beslissingen met betrekking tot de keuze en integratie van energiebesparende gebouwcomponenten te onderbouwen: dergelijke programma’s kunnen gedetailleerde informatie verschaffen over de thermische prestatie van gebouwontwerpen die nog niet zijn gerealiseerd. Zij maken het mogelijk om de prestaties van verschillende ontwerpalternatieven onder precies identieke omstandigheden te vergelijken. Het daadwerkelijke gebruik van dergelijke rekenprogramma’s voor het onderbouwen van de keuze van energiebesparende gebouwcomponenten blijft echter achter bij de verwachtingen. De ontwikkeling van nieuwe gebouwsimulatie programma’s laat een toename van mogelijkheden en complexiteit zien. Deze trend verhoogt echter de noodzaak van zorgvuldig modelleren en de inzet van simulatie-expertise en vergroot daarmee juist de kloof tussen het ontwerpproces en gebouwsimulatie.

Derhalve is het centrale doel van dit proefschrift het *ontwikkelen van een strategie om tijdens het ontwerpproces rekenkundige ondersteuning te bieden voor het maken van een rationele keuze van energiebesparende gebouwcomponenten*. Deze strategie moet worden bewezen aan de hand van de ontwikkeling van een prototype dat de levensvatbaarheid van de strategie demonstreert.

Het werk zoals beschreven in dit proefschrift bestaat uit vier deelonderzoeken, die zich allen richten op het gebruik van simulatieprogramma’s om de keuze en implementatie van energiebesparende gebouwcomponenten te ondersteunen: 1) analyse van het ontwerpproces van huidige energiezuinige bouwprojecten; 2) ontwikkeling van een aanpak om tot een onderbouwde keuze van energiebesparende gebouwcomponenten te komen; 3) analyse van de geschiktheid van tools om het keuzeproces te ondersteunen, en ontwikkeling van ideeën om deze tools te verbeteren; 4) ontwikkeling van een strategie en prototype die tijdens het ontwerpproces rekenkundige ondersteuning bieden voor het maken van een rationele keuze van energiebesparende gebouwcomponenten.

Analyse van huidige energiezuinige bouwprojecten

De analyse van huidige energiezuinige bouwprojecten werd uitgevoerd bij gebrek aan objectieve informatie over de wijze waarop energiebesparende gebouwcomponenten momenteel in de praktijk worden gekozen, en welke rol gebouwsimulatie programma's bij deze keuze spelen. Het doel van de analyse was om voor een aantal recent gerealiseerde prestigieuze energiezuinige gebouwen in Nederland na te gaan hoe de keuze van deze gebouwcomponenten tot stand is gekomen, en welke rol tools speelden bij die keuze.

Om dit doel te bereiken zijn drie case-studies en een enquête uitgevoerd. De cases verschaffen diepgaande informatie over de gang van zaken in drie bouwprojecten; de enquête toont aan dat de bevindingen op basis van deze drie projecten representatief waren voor een grotere groep energiezuinige bouwprojecten.

De bevindingen van de case-studies en de enquête laten zien dat simulatietools geen belangrijke rol spelen bij de keuze van energiebesparende gebouwcomponenten, aangezien deze tools pas na de keuze van deze componenten worden ingezet, en bovendien voor andere doeleinden gebruikt worden (voor optimalisatie en controle van aannames in plaats van voor het onderbouwen van keuzes). Energiebesparende gebouwcomponenten worden momenteel meestal gekozen op basis van analogie: de keuze wordt dan beargumenteerd met het eerdere gebruik van dezelfde energiebesparende gebouwcomponent in een ander gebouw van dezelfde architect of adviseur, of wordt gebaseerd op toepassing in voorbeeldgebouwen. Daarmee lijkt de keuze van energiebesparende gebouwcomponenten vooral plaats te vinden via eenvoudige, heuristische beslissingsregels. Het lijkt echter beter om multi-criteria methoden te gebruiken, om daarmee zeker te stellen dat meerdere eisen aan gebouw en energiebesparende gebouwcomponenten worden meegenomen in het keuzeproces. Om dit te bereiken dienen zowel het keuzeproces als de tools die dat keuzeproces ondersteunen verbeterd te worden.

Een aanpak voor een onderbouwde keuze van energiebesparende gebouwcomponenten

De ontwikkeling van een aanpak voor het onderbouwd kiezen van energiebesparende gebouwcomponenten had tot doel om het keuzeproces te verbeteren. Eisen en randvoorwaarden voor het maken van een onderbouwde keuze zijn in kaart gebracht en benut om bestaande theorieën voor het maken van ontwerpkeuzes te beoordelen. Een prestatiegerichte aanpak voor het kiezen van energiebesparende gebouwcomponenten is ontwikkeld met gebruikmaking van toepasbare elementen uit bestaande theorieën, leidend tot de volgende stappen: het definiëren van een ontwerpruimte, het in kaart brengen van alle relevante functies van de elementen van de ontwerpruimte, het specificeren van prestatie-indicatoren, het voorspellen van de prestatie van alle elementen van de ontwerpruimte voor elk van de prestatie-indicatoren, en het evalueren van deze prestaties om tot keuze van de meest gewenste optie te komen. Deze aanpak rationaliseert het keuzeproces, en maakt de subjectieve waardebeoordeling die daarbij speelt expliciet. Aangezien de aanpak is gebaseerd op prestatievoorspelling biedt deze aanpak een optimaal uitgangspunt voor het inzetten van tools. De levensvatbaarheid van de aanpak is gedemonstreerd aan de hand van een voorbeeld.

Analyse en verbetering van tools

Nadat een procedure voor het maken van een onderbouwde keuze was ontwikkeld was de volgende stap om de tools te verbeteren die deze procedure moeten ondersteunen. De analyse en verbetering van tools ten behoeve van het selecteren van energiebesparende gebouwcomponenten bestond uit de volgende stappen: analyse van de rol van de belangrijkste categorieën van tools (ontwerptools, modelleertools, analysetools, ondersteunende omgevingen en anderen) bij het kiezen van energiebesparende gebouwcomponenten, en

beoordeling van bestaande tools alsmede identificatie van verbetermogelijkheden voor de twee belangrijkste categorieën (analysetools en ondersteunende omgevingen).
Bestaande simulatietools blijken in staat de keuze van energiebesparende componenten aan de hand van de ontwikkelde aanpak te kunnen ondersteunen, maar alleen op voorwaarde dat er voldoende tijd en expertise aanwezig is voor het benodigde modelleer- en simulatiewerk. Ondersteunende omgevingen zijn nog in ontwikkeling en worden nog nauwelijks toegepast.
Simulatietools kunnen worden verbeterd door per tool te analyseren welke gebouw-varianten/systemen met die tool kunnen worden bestudeerd, in termen van welke prestatie-indicatoren. Het identificeren en toegankelijk maken hiervan wordt reverse-engineeren van simulatietools genoemd. Ondersteunende omgevingen kunnen worden verbeterd door hier een set van simulatietools in op te nemen, alsmede een selectiemechanisme dat gebruikers helpt om de juiste (analyse)tool voor een bepaalde (analyse)taak te vinden.

Een strategie en prototype voor het kiezen van energiebesparende gebouwcomponenten
Het doel van het in dit proefschrift beschreven onderzoek was het ontwikkelen van een strategie om tijdens het ontwerpproces rekenkundige ondersteuning te bieden voor het maken van een rationele keuze van energiebesparende gebouwcomponenten, en het bouwen van een prototype dat de levensvatbaarheid van de strategie demonstreert. Om dit doel te bereiken werden de hiervoor omschreven ideeën over verbetering van het keuzeproces en van ondersteunende tools gecombineerd. Deelname in een internationaal onderzoeksproject, het Design Analysis Interface (DAI)-Initiative, verschafte de elementen die nodig waren voor afronding van het onderzoek.

In dit proefschrift is een strategie voor het kiezen van energiebesparende gebouwcomponenten ontwikkeld die bestaat uit de volgende elementen:
1. Energiebesparende gebouwcomponenten moeten gekozen worden volgens een aanpak die bestaat uit de volgende stappen: het definiëren van een ontwerpruimte, het in kaart brengen van alle relevante functies van de elementen van de ontwerpruimte, het specificeren van prestatie-indicatoren, het voorspellen van de prestatie van alle elementen van de ontwerpruimte voor elk van de prestatie-indicatoren, en het evalueren van deze prestaties om tot keuze van de meest wenselijke optie te komen.
2. De belangrijkste belemmerende factoren voor het gebruiken van analyse tools ter onderbouwing van de keuze van energiebesparende gebouwcomponenten zijn de noodzaak tot beschikbaarheid van voldoende tijd en expertise voor het modelleren en simuleren. Dit kan worden opgelost door (vanuit het ontwerpproces) het verzoek tot analyse zo expliciet en eenduidig mogelijk te formuleren. Aan de andere kant moeten simulatietools worden gepreconfigureerd (reverse-engineered) om zo adequaat mogelijk op dergelijke specifieke analyseverzoeken in te kunnen gaan.
3. De aanpak voor het kiezen van energiebesparende gebouwcomponenten moet worden geholpen door toepassing van een ondersteunende omgeving dat een mechanisme aanlevert dat gebruikers eenvoudig toegang geeft tot geschikte simulatietools om de benodigde analysetaken uit te voeren.

Er is een prototype Design Analysis Interface (DAI) – Werkbank ontwikkeld dat de haalbaarheid van betere integratie van simulatietools en ontwerpproces laat zien. Dit prototype is gestoeld op een gelaagde opzet, waarbij de procesdimensie centraal staat. Het prototype demonstreert de levensvatbaarheid van de strategie om tijdens het ontwerpproces rekenkundige ondersteuning te bieden voor het maken van een rationele keuze van energiebesparende gebouwcomponenten. In het prototype verzorgt het concept van analyse functies voor de koppeling tussen proces en simulatietools, door koppeling van specifieke

analysetaken aan voor deze analysetaken geschikte toolfunctionaliteiten. Een analyse functie specificeert precies welke prestatie-indicator berekend moet worden.
Vanzelfsprekend kan volledige onderbouwing van de keuze van energiebesparende gebouwcomponenten pas plaats vinden als de DAI-Werkbank een set van analyse functies bevat die de meest voorkomende prestatieaspecten van gebouwen met energiebesparende gebouwcomponenten dekt, een set van tools die deze analyses ook daadwerkelijk uit kan voeren, en koppelingen tussen die analyse functies en tools.

Verder werk aan de integratie van gebouwsimulatie en ontwerpen van gebouwen vereist de verdere ontwikkeling van ondersteunende omgevingen die het analyseproces beter grijpbaar en bestuurmaar maken, en die toegang geven tot tools die de belangrijke analyse stappen uit dit proces onderbouwen. Het verder reverse-engineeren van simulatietools om bij specifieke analysetaken aan te sluiten lijkt een belangrijke factor bij het verhogen van de inzetbaarheid van deze tools.

Contents

1. Introduction

"And what is good, Phaedrus,
And what is not good -
Need we ask anyone to tell us these things?"

(Robert M. Pirsig)

Humans today live in a built environment: a global man-made system of cities, villages and infrastructure of which buildings are an essential part. Buildings provide shelter against the elements and supply living, working and storage space. As the world population continues to grow, as old buildings need replacement and as requirements for buildings change, the activity of building is a never-ending and highly relevant endeavor.
The making of buildings involves building design and building construction. Building design is the activity that results in detailed drawings and technical descriptions of a building that will satisfy a brief that indicates goals, requirements and evaluation criteria (for instance concerning building function, floor area, life span, architectural image and initial costs). Building construction is the activity that actually produces buildings according to the plans and specifications that result from building design (Müller and Vogel, 1976; Cobuild English Dictionary, 1995). The building industry, including both design and construction, is a major component of the world economy and provides jobs to many people.

The energy use of the built environment has become a major concern. On a global level humanity faces the depletion of fossil fuel supplies; moreover, the use of fossil fuels is an important factor in environmental pollution, and the extraction and transport of fossil fuels often cause harm to local ecosystems. Reduction of the use of fossil fuels and development of alternative energy sources (renewable energy) are the only solution to these problems. As formulated by the World Commission on Environment and Development in its well-known Brundtland-report: 'Energy is necessary for daily survival. Future development crucially depends on its long-term availability in increasing quantities from sources that are dependable, safe, and environmentally sound. At present, no single source or mix of sources is at hand to meet this future need.' (Brundtland *et al.* 1987). A specific concern is that the use of fossil fuels will modify the global climate through the greenhouse effect. The United Nations Environment Programme states that 'the most profound global threat facing humanity today is the prospect that our economic activities will result in global warming, with serious consequences for the earth's entire ecosystem and for the way of life in rich and poor societies alike' (UNEP, 2002a).

The amount of energy used in the built environment is substantial: buildings are omnipresent, and most of them use energy for heating, cooling and lighting. In the member countries of the Organization for Economic Co-operation and Development[1] the building sector accounts for approximately one third of the final energy demand (industry and transport also account for about one third each). In the rest of the world the building and transport sectors are somewhat less important and industry accounts for half of the final energy demand. In the whole world the energy demand in the building sector is expected to increase by an annual percentage of somewhere between 2 and 3 percent over the period till 2010; this increase in demand will be met primarily by fossil fuels (IEA 1996; IEA 2002).

[1] OECD, consisting of the member states and associated states of the European Union, the United States of America, Australia, Canada, Japan, Korea, Mexico, New Zealand, and Switzerland.

The energy problem has had a profound impact on the developments in building during the last three decades. The starting point was the energy crisis of the 1970s which prompted a general use of thermal insulation materials, double glazing and tighter building shells, all of which are now considered standard measures. Since then, researchers and architects have developed an extensive set of specific measures and features that help to make buildings more energy-efficient. Many of those, for instance high-efficiency heating systems or heat exchange systems for ventilation air, are now in common use (see e.g. Althof *et al.*, 2001). In many countries requirements regarding energy efficiency have been included in the building regulations, ensuring that designers and builders address this issue. In order to persuade the industry to go beyond these requirements a range of other incentives is being used, including financial aid, contests for designing energy-efficient buildings, and the assignment of special status (e.g. that of demonstration project) to specific buildings.

The increased attention to energy efficiency of buildings has resulted in a need to understand the principles of heat and mass transfer in buildings, and to apply these principles to the building design process. The key discipline that studies building energy issues is building physics. Building physics covers all physical aspects of buildings: thermal, hygric, ventilation, lighting and acoustical; it provides computational and measurement methods to describe and quantify the related physical phenomena. Regarding building energy issues, the discipline provides computational methods that allow to assess energy use, temperature distribution, and thermal comfort based on human response models. It studies parts of buildings (e.g. thermal bridges, the building envelope or individual rooms), whole buildings and even urban environments. In doing so, building physics provides the knowledge basis for other disciplines including mechanical engineering (the discipline that deals with heating, ventilation and air-conditioning systems), architecture (the discipline that designs buildings), and others.

1.1. Design of Energy-efficient Buildings

Many buildings in today's built environment (worldwide) are considered to be energy-efficient[2] (e.g. Steemers, 1991; Lloyd Jones, 1999; Buis *et al.*, 2000). However, not all buildings perform as well as claimed by their designers (Hartkopf and Loftness, 1999; Yannas, 2003). The actual achieved energy efficiency of many current buildings is neither measured nor computationally quantified. Literature on monitoring and evaluation of building projects is scarce. However, there is no doubt that it is possible to increase the energy efficiency of future new and renovated buildings beyond that of current buildings; in that case however the consequences for other performance requirements (thermal comfort, daylighting, ventilation and related moisture or mold growth problems, etc) need to be addressed.

1.1.1. Energy Saving Building Components

The set of measures and features that make buildings more energy-efficient ranges from general principles (for instance compact building form or zoning) to specific, off-the-shelve systems (for instance heat pumps and solar collectors). Apart from a few exceptions (like zoning) these principles materialize in the form of distinct energy saving building components

[2] Energy efficiency of a specific building needs to be related to an average energy efficiency of any given building stock, or to the efficiency of a reference case. The term is strongly affected by temporal effects: buildings that are energy-efficient today might be found to have an average efficiency - or less - in 10 years.

that are integrated in these buildings. See figure 1.1. Examples of energy saving building components are sunspaces, advanced glazing systems, (additional) thermal insulation or photovoltaic arrays. It is important to note that in general the contribution to the overall energy efficiency of the building (the main objective of their use) provided by these components strongly depends on the thermal interaction between the component and the rest of the building (e.g. the interaction between a sunspace and the adjacent building). Only a few components have a contribution that is relatively independent of the building (e.g. photovoltaic arrays). Also it must be noted that many energy saving building components not only have an impact on energy efficiency, but on other performance aspects like thermal comfort, daylighting, or the ventilation and moisture balance as well. Energy saving building components also play a role in architecture: they are tangible additions to buildings that demonstrate the ambition of the architect (or principal, user etc) to achieve an environmentally friendly building design (e.g. Snow and Prasad, 2002).

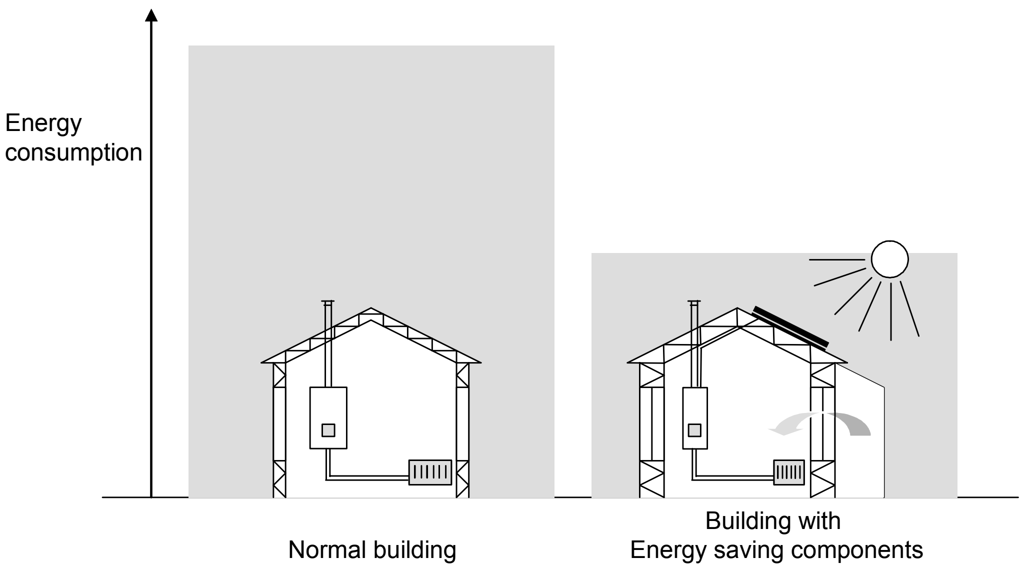

Figure 1.1: Building with energy saving components

Design decisions concerning the integration of energy saving building components in buildings need careful consideration during the building design process. The objective of making a building energy-efficient needs to be balanced with other, often conflicting requirements; especially the maintenance of thermal comfort and a healthy indoor air quality need to be secured. The building in which these components are integrated needs to be safe, reliable and well-controlled (Schwaller, 2003). Many parameters (both related to the component and the building) might affect the actual contribution of the component to the energy efficiency as well as the other performance aspects. The context in which the building will be operated, for instance the climate zone, occupant behavior and local utility billing methods, add to the complexity of these design decisions in particular cases. Finally, studies like Winther and Hestnes (1997) and Mulligan and Steemers (2002) argue that even when focusing on energy efficiency alone there still is a need to balance energy use during operation and embodied energy needed for construction of the building. An integral assessment and trade-off of different relevant aspects is therefore essential.

Yet in many projects the actual contribution of energy saving building components to the energy efficiency of the buildings in which they are integrated remains unclear; the lack of literature on monitoring and evaluation of building projects applies here, too. For many components there is no clear understanding of which parameters (both of the component and of the building) influence the overall energy efficiency of the building, and in what way. For most components the impact of occupant behavior, building control settings, climate conditions and urban context on their performance is unknown. It is difficult to judge how different components interact when integrated into one building, and whether this might make some of those components redundant, or reduce the added value they bring to the building.

1.1.2. Design Support Tools

To be able to make well-considered decisions the decision-maker needs to have information on the actual or expected behavior (energy efficiency, thermal comfort, etc.) of the building. This information can either be obtained from measurements or from computations; measurements can be taken from a real building or from an experimental set-up. Note that the use of experience as source of information for making design decisions actually bases itself on observation from previous buildings, through the same principles of measurements and or computation. The use of experience is limited to similar buildings (containing the same set of energy saving building components) under similar conditions, and is only of limited use when developing new, innovative building concepts.

Computer programs - also named computer applications or just shortly tools - play very divergent roles in the activity of building design, and even broader, the whole building industry. A profound description of many of the different types of tools used in the building industry during the different phases of the life-cycle of a building is given by Eastman (1999, chapter 1), ranging all the way from tools for project cost estimation to tools for facilities management.

The different tools that are used during the building design process can be positioned in a general framework as presented by Hendricx (2000), who discerns three categories of tools: modeling tools, design tools and analysis tools. The first category of modeling tools relates to the use of computers to represent the evolving ideas of a building as an artifact during the design process. These tools allow to graphically capture the (intermediate) design and to capture relevant information like dimensions, shape, materialization etc. The category of design tools uses the computer to generate design alternatives; here the computer helps to modify and improve on existing building designs. This category contains both automated design (where the computer itself generates design alternatives) as well as assisted design (where man and machine collaborate to generate design alternatives). Case-based reasoning systems, approaches in artificial intelligence and expert systems are tools that belong in this category. Finally, the category of analysis tools uses the computer to evaluate buildings or building designs. Here the computer helps to assess properties and performances. A subset of the set of analysis tools are building performance simulation tools. Building performance simulation deals with different kinds of building performance aspects (in contrast to analysis tools that deal with building properties). The most important performance aspects are energy transfer, structural stability, acoustics, (day)lighting, indoor air quality and air flow. Of these, building energy simulation and structural stability are the most prominent fields. Building performance simulation can be used to study existing or future buildings; it plays an important role in building research.

All three main categories of tools are relevant when it comes to integration of energy saving building components into buildings. Modeling tools help to describe which energy saving components are used in a building, and how these are integrated. Design tools help the design team to generate building design alternatives that include energy saving components. Analysis tools help to assess the performance of buildings with energy saving components. Currently most of the tools that deal explicitly with energy saving components are analysis tools.

Research and development in the field of building energy simulation have produced a large number of energy-related computer programs. These tools range from simple to sophisticated computer programs, and range from tools that consider one performance aspect only to tools that take a more integral view. Also, they might be intended to be used by designers, consultants, or might be developed for use by experts working in a research context. A good overview of available tools is provided by the US Department of Energy building energy software tools directory on the internet (DOE, 2002), which lists some 200 different applications. There is little common ground across the multiplicity of these tools as they typically have been developed from different backgrounds and with different use objectives in mind. As a result this large set of tools can be used for a multitude of functions, which may or may not be relevant for a design team when faced with energy-related design decisions.

In current building practice energy analysis tools are mostly used by consultants working in the domain of building physics or heating, air-conditioning and ventilation (HVAC) systems. These consultants can play roles as member of the design team, or as specialist solving problems in existing buildings, sometimes in the context of legal matters. In a design context one of their main tasks is to help the design team to make well-informed decisions regarding the selection of energy saving technologies.

However, there are concerns about the actual role of computational assessment in the building design process. Many researchers continue to observe a lack of integration of analysis tools and the building design process (e.g. Degelman and Huang, 1993; Radford, 1993; Aho, 1995; Mac Randal, 1995; Robinson, 1996; Hand, 1998; Augenbroe, 2001; Donn *et al.*, 2001). There is doubt whether existing computational tools are used at all during the design process, and if so, whether the capabilities of the tools are fully exploited. The suitability of current computational tools to support the building design process remains an issue of debate; yet it might very well be possible to modify existing tools or develop new tools that fit better into the design process.

1.1.3. Room for Improvement

In spite of all efforts achievements so far in developing energy-efficient buildings, energy saving building components and tools to support the design of energy-efficient buildings, there are both opportunities and needs for further improvements. Opportunities arise from new technological inventions and the ongoing development of existing technologies. The needs are created by ever-increasing environmental problems, which are very clearly stated by the United Nations Environmental Programme (2002b): ‘There has been immense change in both human and environmental conditions over the last 30 years. In an unprecedented period of population increase, the environment has been heavily drawn upon to meet a multiplicity of human needs. In many areas, the state of the environment is much more fragile and degraded than it was 30 years ago.’

1.2. Problem Description

The general problem addressed in this thesis is integration of building performance analysis tools and the building design process. Although building performance analysis can be expected to be an essential part of the building design process, actual application of analysis tools to provide information to support building design decisions does not live up to this expectation. Still there are compelling reasons to strive for a better integration of building analysis tools and building design process:

- Building energy analysis tools can provide essential and detailed information about the thermal performance of buildings that have not yet been built. This allows objective comparison of different design options (energy saving technologies), which allows design teams to make better informed design decisions, and contributes to preventing over-engineering of buildings from an energy-saving point of view[3]. This will also help the design team to justify their choices for the principal and, where needed, for legislative bodies[4].
- The same detailed performance information can be used to achieve a well-considered integration of any chosen energy saving technology in the building design, through optimization of relevant parameters. This can be expected to lead to further increases in the energy efficiency of buildings.

Building designers and consultants are well-aware of the potential benefits of integration of building performance analysis tools and the building design process (e.g. Brouwer, 1996; Stoffels, 1999; Jones and West, 2001; Rooijakkers, 2002; Moushed, 2003; Milne, 2003; Chown, 2003; Hobbs *et al.*, 2003). This is apparent through the efforts invested in the developments around integral design, strategic design, collaborative engineering etc in building design[5].

Experts in the field of building performance analysis tools, e.g. Crawley and Lawrie, (1997), Hand (1998), Augenbroe (2001), Clarke (2001) and Donn *et al.* (2001) are focusing on this specific integration issue and voice a continued need to improve the role of building analysis tools in the building design process. Common findings in their work are the need to pay attention to the process dimension (the activities that make up the design process, their interdependency, sequence(s) of occurrence etc), an issue missing from most previous efforts; the need to accommodate and support changing practices in the building design process; and the anticipation of a profound impact of the internet on integration of building design process and building performance analysis.

It is noted that many researchers (e.g. Degelman and Huang, 1993; Augenbroe, 1994; Aho, 1995; Augenbroe, 1995; Hand, 1998; André *et al.*, 1999; Hobbs *et al.*, 2003) have already tried to achieve a better integration of building performance analysis and building design process, so far however without overwhelming success. Still, these efforts have revealed some of the potential causes for the lack of integration, like an unavailability of tools and/or models when needed, a high level of expertise needed for full use of simulation tools, high costs (both time and money) connected to simulation efforts, and problems related to data exchange (mismatch between available information about an (intermediate) building design and

[3] Developing buildings that contain an excessive number of energy saving measures.

[4] Elovitz (2002) states that for the design and integration of HVAC systems, the system selection report is the most important document provided by the HVAC consultant.

[5] Note that integral design, strategic design etc are still under development, lacking a clear definition and not yet providing clear-cut approaches that can be used in practice; see e.g. Quanjel and Zeiler (2003).

information requirements by simulation tools). A further discussion of these research projects and their findings can be found in chapter two.

Because of the apparent difficulties of integration of building performance analysis and building design this thesis focuses on one specific type of building design decision: the selection of energy saving building components.

This focus reduces the complexity of building design in general to one particular aspect where building energy analysis tools can play an important role in providing computational support for making well-informed building design decisions. The selection of energy saving building components is a relevant design decision problem that affects the energy efficiency of the entire building, as well as other performance aspects like thermal comfort. The choice of which energy saving component(s) will be selected for a particular building is the prime decision that affects the contribution of this component to the energy efficiency of the building; optimal integration of this component in the building takes place within the boundaries that are defined by the choice of the energy saving building component.

1.3. Goal

The central goal of this research project is the *development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components*. This strategy needs to be substantiated by development of a prototype (which can be a new type of tool or support environment) that demonstrates the feasibility of the strategy.

The public relevance of the development of this strategy is a contribution that enhances decision-making during the design of energy-efficient buildings. In a general sense this contributes to increased attention for building performance and helps design teams to respond to the demand for high-quality buildings. The specific focus on selection of energy saving building components contributes towards making efficient use of fossil and alternative energy sources in buildings, and to the overall goal of managing the impact of the built environment on global energy use[6].

The scientific relevance of the development of this strategy lies in a contribution towards solving the long-standing problem of integration of building simulation and building design process. Yet it is noted that based on one thesis alone full integration[7] cannot be achieved; this will only be attained by the combined efforts of many actors over many years.

1.4. Thesis Outline

The research presented in this thesis concerns the fields of building design and building simulation; these fields underlie all research activities reported here. The aim is to improve their integration.

The outlines of this thesis are based on the following four issues:

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[6] Note that in this thesis the focus is on energy efficiency as related to energy use during operation, and not on energy efficiency as related to life cycle analysis.

[7] In the sense that a set of simulation tools is regularly used during building design projects to underpin a whole range of decisions made by the building design team.

- Discussion of the context and starting points for the research, based on a review of previous work on the integration of building design process and building simulation;
- Analysis of the current situation, through an analysis of integration in current building design projects (AS-IS);
- Innovation, through development of ideas on how to obtain improved integration of building simulation and building design process (TO-BE);
- Realization, through the development of a prototype that demonstrates this improved integration.

Based on this structure the content of the following chapters is as follows. Chapter two reviews previous work on integration of building design process and building performance analysis; it provides a background on building design, energy-efficient buildings, and then focuses on integration of building design process and building simulation in the light of selection of energy saving building components. This chapter is based on a study of literature and on review of existing energy saving building components and building energy simulation tools. Chapter three presents an analysis of selection of energy saving building components in actual energy-efficient building design projects, and the role of building energy simulation tools in this selection. The research methods applied here are case-studies and a survey. Chapter four presents the development of an approach to improve the procedural aspects of the selection of energy saving building components by applying performance-based theories to this selection. Chapter five analyzes possibilities to improve the usability of tools to better support the selection of energy saving building components in the future. Chapter six combines the results of the research and development work of the chapters four (process) and five (tools) into the strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components that is the goal of the research, and develops a prototype that demonstrates feasibility of underlying ideas. Finally, chapter seven completes thesis by providing a summary of the work, conclusions of the research, discussion of future challenges, and concluding remarks.

The overall structure of the thesis is represented by figure 1.2.

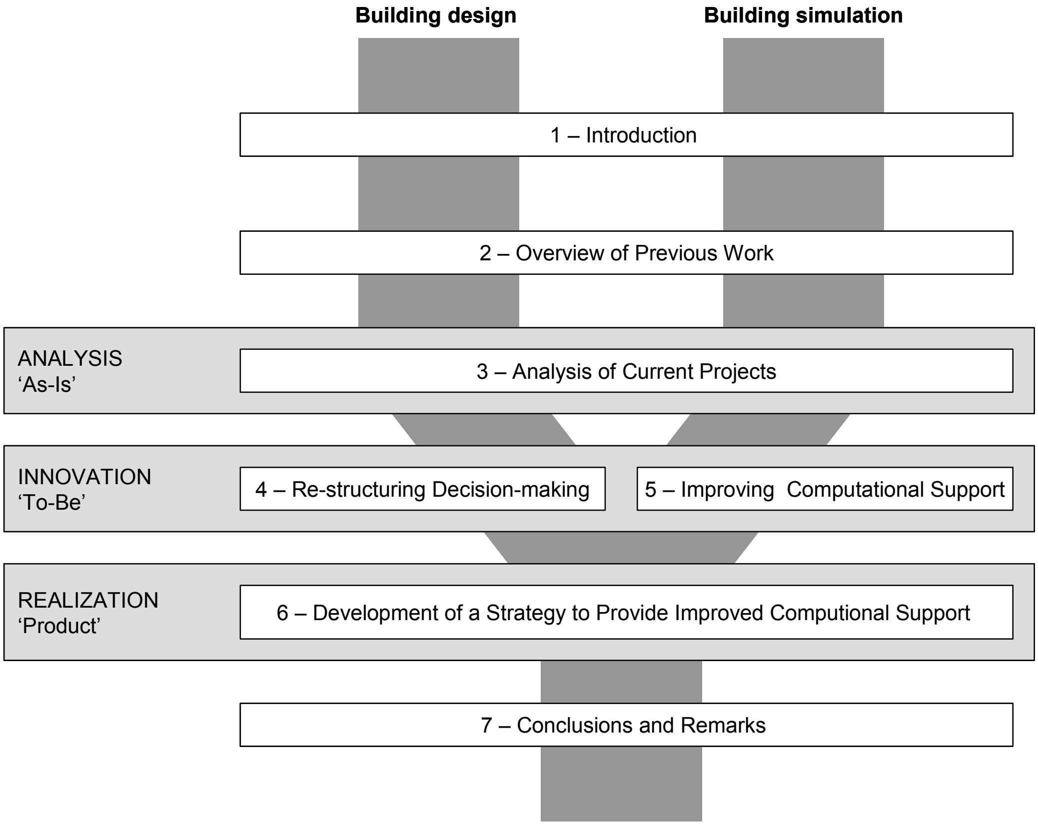

Figure 1.2: Structure of the thesis

2. Previous Research in Integration of Building Simulation and Building Design

"... there is a knife moving here. A very deadly one; an intellectual scalpel so swift and so sharp that sometimes you don't see it moving. You get the illusion that all those parts are just there and are being named as they exist. But they can be named quite differently and organized quite differently depending on how the knife moves. ... It is important to see the this knife for what it is and not to be fooled into thinking that motorcycles or anything else are the way they are just because the knife happened to cut it up that way."

(Robert M. Pirsig)

This chapter gives an overview of previous work in the field of integration of building performance simulation and building design. Paragraph 2.1 provides a background on building design, paragraph 2.2 on design of energy-efficient buildings in particular; building (energy) performance simulation is treated as integral part of both subjects. Paragraph 2.3 presents earlier work and the state-of-the-art for integration of building performance simulation and the design of energy-efficient buildings. In order to position this state-of-the-art in the field of engineering design in general some integration efforts in other disciplines that involve both design and simulation are included. Paragraph 2.4 summarizes the findings and presents conclusions. Paragraph 2.5 closes the chapter by identifying the research questions that will be addressed in the rest of the thesis. The content of this chapter originate from literature review, internet search, study of energy saving building components and study of existing computational tools (de Wilde, 1998; de Wilde *et al.*, 1998).

2.1. Building Design

Building design can be defined as the development of building plans and building specifications that meet the requirements of a principal and that satisfy the rules provided by the government[8]. Building design is an activity that takes place at the start of the life cycle of buildings: it is triggered by the arising of need for a new building and followed by building construction, use, possible renovation and reuse, and finally demolition. Building use can last decades, sometimes even centuries; hence in general design decisions made during the design process will have a long-lasting impact (Müller and Vogel, 1976; Cobuild English Dictionary, 1995).

2.1.1. Building Design Process

Building design changes with time, as do the roles of the participants in the building design process. For a long time buildings were relatively simple structures that could be designed as well as constructed by experts known as master builders. As buildings became more complex design and construction were separated; building design now is assigned to an architect, while construction is assigned to a contractor. Next, building components became more complex, resulting in the need for specialists like structural engineers, mechanical engineers, electrical engineers and building physicists to support the architect. The construction process has become more complex, too. This has resulted in general contractors employing

[8] Governments issue building regulations to ensure safety, usefulness, energy efficiency etc (e.g. VROM, 2002).

subcontractors, and in the introduction of construction managers who supervise the whole process. This trend towards specialization is continuing today. Overall this makes projects more and more complex, requires larger investments, and sees more disciplines and participants being involved. At the same time these projects are carried out under tighter schedules and with higher quality requirements (Merritt and Ambrose, 1990; Eastman, 1999, Alsawi and Ingirige, 2003).

Within today's building design process several stages can be distinguished. The following phasing is in common use: feasibility study, conceptual design, preliminary design, final design, and preparation of building specifications and construction drawings. This phasing is based on recognizable end products for each phase. The phase of feasibility study encompasses the preparations that precede the actual design work. The phase of conceptual design is the phase in which an initial design is created; the final result is a conceptual plan, sometimes named sketch design or structural design. During the phase of preliminary design this initial design is elaborated, resulting in provisional design drawings; in the phase of final design this provisional design is fixed and laid down in final design drawings. In the phase of preparation of building specifications and construction drawings this final design is completed with the development of listings of building parts, tender documents and so forth.

The main actors in the building design process are the principal, the architect and specialists. The principal is the actor that commissions the building design; the actor designing the building is mostly an architect. Depending on circumstances (building size, building complexity, capabilities of principal and architect) specialists play a role in the design process, too: structural engineers, mechanical engineers, consultants for building physics, project managers, and building contractors. These parties can collaborate in different structures. Coordination of the building design process can be carried out by different actors (principal, architect, building contractor) and some of the parties might work together in (sub)teams. It is important to note that the composition of project teams change from project to project (de Bondt *et al.*, 1990; Merritt and Ambrose, 1990), as do the design management structures. The different actors can play a role in all phases, but normally the earlier phases are dominated by activities of the principal and the architect, whereas the activities of the specialists tend to take place in the later phases. Some important approaches in structuring and managing the design process are design-build or turnkey (where one design team member takes overall responsibility for realization of the project, including design and construction) and in-house projects (where the whole design and construction process is carried out by one large company that has all relevant expertise).

New, innovative technologies impact the building design process. Although the building industry is slower than most other industries in taking up new technologies developments in process management, new systems and components, new construction materials and especially the rapid developments in information communication technology (ICT) continuously change the context in which building design and construction takes place. Computers now are in common use for data keeping, for making calculations and for analyzing complex situations, and for representing building design by means of two and three-dimensional drawings, building perspectives and renderings. Whereas these representations now are still printed on paper, it is expected that there will be a transition to a full electronic/digital representation (Eastman, 1999; Holness, 2003; Alsawi and Ingirige, 2003; Husin and Rafi, 2003). The internet allows electronic communication, electronic commerce and electronic data exchange to have an increasing impact on the building design process (Georgia Institute of Technology, 2002).

2.1.2. Rational Design Decision-making

Design is an activity that is important in many disciplines. Especially the engineering disciplines have yielded an important body of knowledge on making rational design decisions. The building industry is aware of this body of knowledge, and efforts are under way to apply this knowledge to building design decision making. The main driving force is the International Council for Research and Innovation in Building and Construction (CIB), which published an important report named 'Working with the performance approach in building' on this issue in 1982 (CIB, 1982). However, this report emphasizes real testing (according to so-called Performance Test Methods or PTMs) rather than analysis of building performance using computer tools. The main work in the field is currently undertaken by the CIB Program on Performance-Based Building (PeBBu); information on the latest developments can be downloaded from the PeBBu website (CIB Program on Performance-Based Building, 2002).

The body of knowledge on making rational design decisions from a performance point of view originates from the ideas presented by Herbert A. Simon in 'The Sciences of the Artificial' (Simon, 1969). This work introduces an outline for a science of design, based on an analytic, partly formalizeable, partly empirical body of knowledge about the design process. It discusses how probability theory and utility theory can be applied to design in order to make a rational choice among given (design) alternatives. Since then work in the fields of systems engineering (e.g. Blanchard and Fabrycky, 1998) and decision theory (e.g. Keeney and Raiffa, 1993; French, 1993) has been added to this framework. This 'science of design' now is part of more general design methodology (e.g. Cross, 1994; Van der Kroonenberg and Siers, 1992; Roozenburg and Eekels, 1991).

Design methodology provides a body of knowledge on the design process. It describes the thoughts and actions that make up this design process and provides rules and methods for designers. Some of the main features of design methodology concern the clarification of design objectives, setting of (performance) requirements, generation of a design or set of design alternatives, evaluation of this design, and improvement of design details (Cross, 1994; Van der Kroonenberg and Siers, 1992; Roozenburg and Eekels, 1991).

Design can be defined as devising (human made) systems. The theory of systems engineering provides a body of knowledge to carry out system design: systems engineering is the application of the scientific method[9] to the design, development, implementation and control of systems, where a system is a set of interrelated components working together towards some common objective or purpose (Blanchard and Fabrycky, 1998). System engineering can be applied to many disciplines; however, though there is general agreement on the principles and objectives of system engineering, each application will strongly depend on this discipline and the background and experiences of the participants, as well on the complexity of the system (Blanchard and Fabrycky, 1998; INCOSE, 2003). The applicability of systems engineering to the building design process has been demonstrated in the context of cost control; according to Merrit and Ambrose (1990) systems engineering in building design can be achieved by adaptation of the traditional design procedure.

[9] Basically the scientific method consists of the following steps: 1. collection of data, by means of observation of some sort of phenomenon; 2. formulation of an hypothesis capable of predicting future observations; and 3. testing of this hypothesis through experiments and new data collection.

Systems engineering addresses all major life-cycle processes of systems: systems design, development, production/construction, distribution, operation, maintenance/support, phase-out and disposal. In this thesis the focus is on system design.

A system consists of components; the components have attributes (properties) and are linked by relationships. When taking a systems view one can distinguish sub-systems and aspect-systems. Sub-systems are those parts and sections of the system that may exists in any stage of the building design and construction process. In other words: a sub-system is a set of components from the system, in which all relationships between this subset of components is maintained. Aspect-systems relate to a specific function of a system and in principle most parts of the system contribute in some way to that function. In other words: an aspect-system is defined by focusing on specific relationships, and mostly all components of the system play a role. Figure 2.1 presents the sub-system view and aspect system view in graphical format. The distinction of sub-systems and aspect-systems bounds the study of a system and provides a handle on important relationships; this helps the systems designer in achieving a satisfactory result (Blanchard and Fabrycky, 1998).

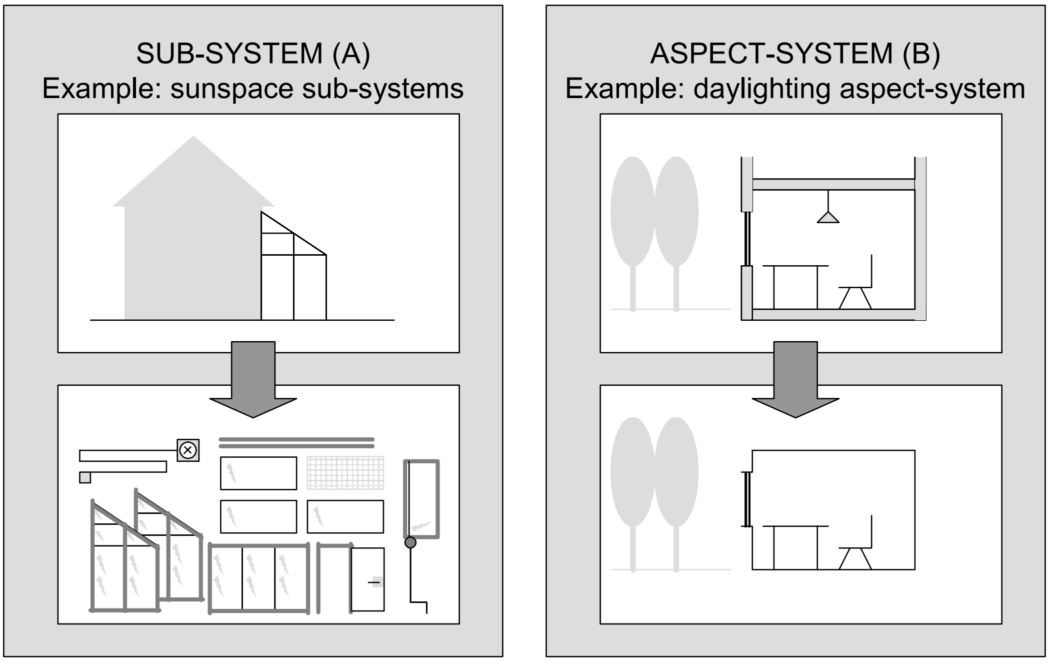

Figure 2.1: Sub-system view (A) versus aspect-system view (B)

Systems are designed to fulfill a function or role. Therefore, design decisions about systems should be based on how well a proposed system will perform this intended function or role. The performance of a system depends on the interaction of a system with its environment. Here two worlds come together: the inner environment of the system (substance and organization of the system itself, sometimes named inner structure) and the outer environment (the surroundings of the system). Only when the inner environment of the system is appropriate to the outer environment will the system serve its purpose (Simon, 1969). The system communicates with the outer environment through input and output; the inner environment includes system states and state transition mechanisms. The inner environment reacts on input by transforming states in successor states and output (Zeigler et al, 2000).

Note that performance of a system (because of the interaction with the environment) is not an attribute/property, but a function over the attributes/properties.

In order to study how well a design will perform its function or role one must qualify and quantify its performance. Since the system is still being designed and hence in most cases the interaction between system and environment cannot be studied in practice, the definition and execution of a (virtual) experiment (simulation) becomes essential to predict performance. In order to develop a meaningful experiment expert knowledge about the components, attributes and relationships between components is vital. The experiment will generate a set of observable states and output. From these a measure for how well the system performs its function must be derived; doing this results in quantification of the performance of the system in a specified performance indicator. In the experiment all observations are ordered according to a time base (Zeigler et al, 2000).

Based on quantification of the performance of all design alternatives a decision must be made to select the design option that has the range of outcomes (and associated probabilities) that are most desired. This involves determination of the values of all design options; a value indicates the attractiveness of each design option in relation to the objectives and constraints.

Decision theory is concerned with making rational choices between alternatives by applying (mathematical) methods. Within decision theory a distinction is made between single- and multiple-attribute decision problems, depending on the number of descriptors (attributes) that are needed to specify the consequences of a decision. Also a distinction is made between problems under certainty or uncertainty. For problems under certainty the consequence(s) of a decision are known; for problems under uncertainty there is a range of possible consequences. Making decisions under uncertainty involves taking (or limiting) risks. Decision methods that provide a preference order are named ordinal methods; methods that provide a preference order as well as a measure of the strength of these preferences are named cardinal methods (Keeney and Raiffa, 1993; French, 1993).

2.1.3. Quality Demands

Buildings today have to meet increasingly stringent quality demands. On the one hand these quality demands are imposed by governments worldwide, who are responsible for the safety, healthiness and functionality of buildings, and who want to achieve a range of objectives like reduction of CO_2-emissions and limitation of the dependence on (imported) fossil fuels, but also objectives like ensuring employment and economic growth. On the other hand future occupants strive for a high standard of living and expect new buildings to be thermally, visually and acoustically comfortable, as well as pleasant. Building designs must meet all of these quality demands (Hartkopf and Loftness, 1999). While these demands can be ordered according to importance - safety first, then reliability, then control, and finally efficiency (see e.g. Schwaller, 2003), all these demands must be met. At the same time design costs, construction costs, maintenance and operation costs need to be controlled (Merritt and Ambrose, 1990). The increasingly stringent quality demands make building design a more complex activity. This complexity turns more and more design processes into team work, with specialists collaborating and contributing to the design. Team work calls for a different organization of the design team, resulting in changing roles of the design team members (Cross, 1994; Jones and West, 2001). Note that quality of buildings is difficult to measure, since it always implies a subjective judgment. In order to eliminate this subjective element one needs to look at the underlying building performance that is being judged.

All over the world the building codes are more and more formulated like performance requirements. Performance-based codes replace prescriptive codes, that have been found to have major disadvantages. Prescriptive codes are a barrier to innovation: improved or cheaper products may be developed, yet their use might not be allowed if construction is governed by prescriptive codes and standards. Prescriptive codes also are a barrier for international trade in building products, since they make it difficult to establish the equivalence between the two sets of criteria of two different countries; it is often very complex to show that one country's accepted solution would equal the implied performance level required by the other country (Foliente, 2000). Performance-based codes do not have these disadvantages. A good example of a performance-based code is the new Dutch building code that is effective per January 1st, 2003 (VROM, 2002).
Most building codes, whether prescriptive or performance-based, have specific requirements regarding the energy efficiency of the building. Embedded in the new Dutch building code is an energy performance evaluation method named EPN (NEN, 2001a; NEN, 2001b). Within Europe efforts are under way to harmonize national energy performance requirements by means of the European Energy Performance of Buildings Directive (EPBD). In the US performance-based codes are still under development; however, the LEED (Leadership in Energy & Environmental Design) rating system (U.S. Green Building Council, 2001), a voluntary consensus-based national standard for developing high-performance sustainable buildings, is rapidly gaining ground and becoming an instrument of which the use is required by many principals.

Three main approaches are available for assessing the performance of buildings or parts of buildings:

- Monitoring allows to assess building performance through direct observation of the behavior of real buildings under operational conditions. The data that is collected by monitoring can provide valuable insights in the functioning of the building, sometimes allowing to improve the building or building control settings. However, monitoring is expensive, while the operational conditions like climate and occupant behavior are difficult to control. Moreover, because of the complex interaction between the building and its (energy saving) components, it is difficult to translate the findings for one building to new and different building designs.
- Experimental set-ups allow to measure the behavior of a part of the building (for instance a window or segment of the façade), while reducing costs and improving control over the experimental conditions (like the control of temperatures and air pressure in a climate chamber). Still, the translation of the findings of an experimental set-up to the behavior of a complete building remains a delicate issue.
- An alternative to measurements on either real buildings or experimental set-ups is computational assessment. Computational assessment (re)produces building behavior using a (set of) mathematical equation(s). These equations sometimes can be solved manually, but in general computer programs are used to deal with the more complex sets. Computational assessment of building behavior aspects using computer programs is named building performance simulation. Computational assessment is inexpensive when compared to measurements. Moreover, it is the only option that allows to compare the behavior of different buildings and building variants under exactly identical conditions. Importantly, it is the only method available that allows accurate prediction of the behavior of an unrealized building. Because of this, computational assessment now is the most widely used method.

Of course these categories can be mixed and/or combined to meet the specific needs and context of a building assessment situation (for instance a mix of monitoring and computational assessment to get a fast and inexpensive indication of energy consumption and thermal comfort in a building).

2.1.4. Building Performance Simulation

Simulation in general is the reproduction of the physical behavior of a system (for instance a building, an aircraft or a chemical production plant), nowadays mostly using a computer. Simulation is based on physical modeling of the system, development of mathematical equations that describe the behavior, solution of these mathematical equations, and presentation (visualization) of the results.

Physical modeling idealizes, quantifies and simplifies the behavior of the real world system by description of this system as a set of internal variables, distinct system boundaries, and external variables; the result is named a physical model. Definition of the set of relations between the variables of the physical model results in a mathematical model; sometimes the development of the mathematical model involves making numerical approximations. In order to solve the equations that make up the numerical model these are coded in some programming language and subsequently run as a computer program (commonly named tool). A particular instance of a system and its context in a computer program make up a numerical model. Output can be presented both in numerical and graphical format (Bland, 1992; Bosgra, 1996).

Building simulation is the domain of simulation that studies buildings or building sub-systems. The most relevant behavioral aspects studied in building simulation are heat transfer, (day)lighting, acoustics, and air flow. The principal actors in building simulation are tool developers, building researchers and consultants. The field of building simulation first emerged during the 1960s. In this period research efforts focused on the study of fundamental theory for building simulation, mostly for energy transfer. During the 1970s the new field matured and expanded, driven by the energy crisis of those years. Most research was devoted to the development of algorithms for heating load, cooling load and energy transfer simulation. In the 1980s the effects of the energy crisis waned. However, this effect was compensated by the advancements in personal computers, which made building simulation widely accessible. As a result, research efforts now concentrated on programming and testing of computational tools. In the same period, natural selection set in: only tools that had active support from their makers (maintenance, updating, addition of desired new features) were able to survive. Finally, during the late 1980s and the 1990s the field of building simulation broadened with the development of new simulation programs that where able to deal with lighting, acoustics and air-flow problems. A growing global concern about environmental issues caused renewed interest in building simulation (Augenbroe, 2000; Hong *et al.*, 2000).

A good overview on developing trends in building simulation is provided by Augenbroe (2001). The following important trends are identified:

- continuous efforts in the field of tool interoperability. These efforts aim at the development of a general data model (product model) for buildings that can be used to

store information and provide data for an array of different building simulation tools (e.g. Bazjanac and Crawley, 1999; International Alliance for Interoperability, 2002)[10];
- the development of modular computer programs. Here the main objective is to make simulation tools more transparent, easier to maintain and easier to extend than the current monolithic tools; the main enabler for this development is object oriented programming (OOP) (e.g. Sahlin, 1996);
- developments in the field of coupled simulation, where for instance thermal and air-flow problems are simulated simultaneously (e.g. André *et al.*, 1998; Djunaedy *et al.*, 2003; Carrilho da Graça *et al.*, 2003; Haves *et al.*, 2003; Citherlet and Macdonald, 2003; Zhai and Chen, 2003);
- an increased impact of the internet on building simulation, affecting all aspects from simple information exchange to the way simulation is offered (for instance distributed simulation and commercial, web-hosted simulation services) (e.g. Primikiri and Malkawi, 2001);
- a number of other ongoing developments, like validation, error diagnostics, sensitivity, uncertainty and risk analysis, standard post-processing, animation etc.

Within building performance simulation most attention so far still goes to energy-related issues. Building energy simulation studies the thermal aspects (heat flows, temperatures, energy consumption) in buildings. Closely related aspects that have a strong impact on energy use and thermal comfort are air flow and (day)lighting, since air flow affects ventilation losses, daylighting is coupled with solar gain, and artificial lighting contributes to internal gain. A good in-depth discussion of the basics of building energy simulation is provided by Clarke (2001).

In buildings, heat transfer can be studied at different levels of detail: one can discern heat transfer at building component level, at room or zone level, at the level of whole buildings, or even at an urban scale. Additionally, one can study heat transfer in one, two and three dimensions.
The most commonly used building energy simulation types are the following:
- steady state models, that neglect the dynamic aspects of heat transfer, but are appropriate for the evaluation of situations where time has little impact;
- simple dynamic models (sometimes named semi-dynamic models), which take into account some parts of dynamic heat transfer, for instance by using an average outside temperature, an (imaginary) static heating season, or utilization factors. These models can be based on the results of measurements or on the results of more advanced computational models;
- dynamic models, which fully mimic the dynamic aspects of heat transfer; most employ numerical techniques like the finite element and the finite difference method.

Good and well-known treatises on heat transfer at building and building component level are Duffie and Beckman (1991) and the ASHRAE handbooks of fundamentals (ASHRAE, 2001), HVAC systems and equipment (ASHRAE, 2000) and HVAC applications (ASHRAE, 1999).

[10] The concept of one general data model to store all building design information is not unchallenged; e.g. Augenbroe and Eastman (1998) and Mahdavi (2003) provide critical remarks on the use of one model to support different performance analysis tasks.

2.2. Energy-efficient Buildings

Within this changing context of building design energy efficiency makes its mark in architecture; the subject gets attention in architectural journals like World Architecture (Lloyd Jones, 1999) or The Architects' Journal (Evans, 1997), and is a part of most contemporary architectural educational programs. There are special design competitions and programs that have the objective of developing the most energy-efficient building conceivable, like the development of the IEA task 13 advanced low energy dwellings (Hestnes, 1997) and the Solar House Programme of the European Union (Lewis and Fitzgerald, 1997). Dedicated organizations like PLEA (Passive and Low Energy Architecture) discuss and boost the design of energy-efficient buildings (PLEA, 2003). In daily practice all architects have to meet the demands of their principals and future building occupants for energy efficiency. Moreover, most industrial countries now have building regulations that enforce at least a basic set of energy conservation measures. Sometimes additional programs try to stimulate building design teams to do better than just meet these requirements (Bosselaar, 1997). The field of energy-efficient building design is constantly evolving, requiring attention during each new project (Yannas, 2003).

Terminology regarding the design of energy-efficient buildings needs special attention. Irrespective of the interest in energy efficiency all buildings must satisfy a principal's brief, which includes functional, financial and architectural requirements. Because of this the widely used term 'energy-efficient design' is dangerous: it creates the impression that energy efficiency can be the sole design objective. On the other hand terms like 'integral design' that reflect the multiple objectives of the design process lack in focus. Hence this thesis makes consistent use of the term 'design of energy-efficient buildings'.

Within the overall design process the following strategy provides a first step towards achieving energy-efficient buildings:

1. minimize the overall need for heating, cooling and lighting;
2. utilize renewable energy sources to provide the remaining heating, cooling and lighting needs;
3. use fossil fuels efficiently to provide in any remaining need, and only if no renewable sources are available.

Some design solutions that are in line with this approach have become self-evident: use of thermal isolation, minimization of air gaps, avoidance of thermal bridges, solar orientation and application of energy-efficient HVAC-systems are daily practice. Increasingly, use is made of additional energy saving building features or components to make buildings even more energy-efficient.

2.2.1. Energy Saving Building Components

Energy saving building components can be defined as (integrated) building components that are designed to make buildings more energy-efficient. They can be based on all of the before-mentioned principles and help to minimize the energy needed by the building for heating, cooling and lighting, help to access renewable energy sources, and help to make more efficient use of fossil fuels. This section provides a brief discussion of the principles underlying existing energy saving building components that is based on this classification. A listing of the most important main types of energy saving building components that are currently available to building designers is provided in appendix A.

Regarding terminology the word component needs further discussion. According to the Cobuild English Dictionary (1995) 'the components of something are the parts it is made of'. This thesis will use this description and define building components as the parts of which a building is made. The word component can also be used in a classification of building parts that ranges from raw materials via elements, components, (sub)systems to whole buildings (e.g. Eekhout, 1997; Nasar *et al.*, 2003). In such a classification many energy saving building 'parts' will be on the component level; however, for convenience the term will be taken to cover energy saving technologies on other aggregation levels as well. Also, it is noted that in phases of the design process were the design is still materializing and the final form of energy saving technology is not yet specified, it would be more appropriate to speak of energy saving features rather than energy saving components. Again, for convenience the term component will be used in this thesis to cover such energy saving features as well.

Energy saving building components that minimize the energy needed by buildings are based on their influence on the energy flows caused by transmission, ventilation and infiltration, utilization of internal gains, storage of surplus energy to cover later energy needs, and maximal utilization of daylight.
Transmission is the heat transfer through the building shell by means of conduction (internally), and convection plus long-wave radiation (at the surface). Ventilation is the transfer of air from one space (both inner spaces and outer spaces) to another, which results in heat transfer as well; if air transfer is not intentional but is the result of air moving through cracks etc this is called infiltration. Internal gains are the result of the heat produced by humans, appliances etcetera. Storage takes place in the construction, furniture or specific elements that can contain energy.
Typical energy saving building components in this category include thermal insulation layers, heat exchangers for ventilation, enclosed porches, thermal mass (water tanks, rock-beds, aquifers), phase-change materials, and reflecting blinds, lightshelves etc.

Energy saving building components that access renewable energy can be based on several energy sources. See figure 2.2. The most common ones are solar energy, ambient heat, and wind energy. In most countries other sources like biomass, hydropower and geothermal power are used relatively rarely, since their availability is highly variable.
For solar energy a distinction is made between passive and active use. Passive systems exploit solar energy applying simple devices, materials and concepts. Strictly speaking passive systems do not use auxiliary energy; however, small amounts (like electricity needed to drive a ventilator) are often accepted. Passive systems can be subdivided in direct, indirect and isolated systems. In direct systems solar radiation enters the target space, where it is converted to heat. In indirect systems the conversion takes place in another space, which is named the collector; heat is transported to the target space using a convective or conductive medium. In isolated systems the target space and collector are separated by physical separation or thermal insulation. Active systems exploit solar energy with technical installations; if needed they use auxiliary energy. Active systems can be subdivided into photothermal systems, which provide heat, and photovoltaic systems, which provide electric power.
Typical energy saving building components in the category of components that access renewable energy include skylights, trombe-walls, glazed balconies or atria (all passive solar), warm-water collectors (active solar, thermal), PV-arrays (active solar, photovoltaic) and wind turbines (other source).

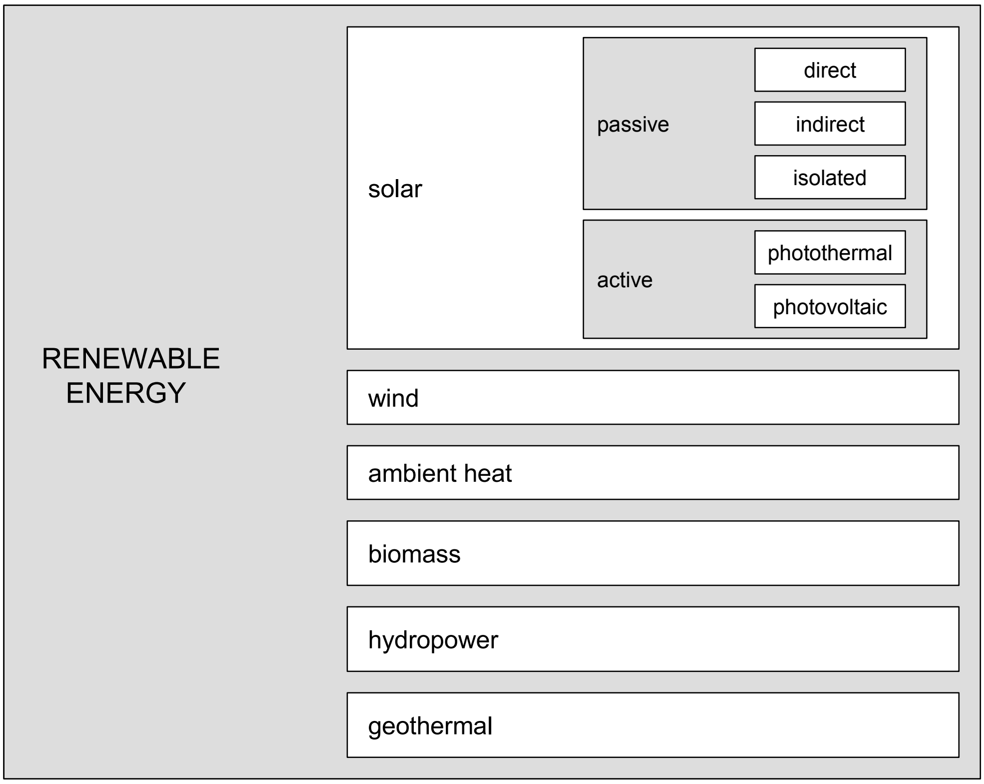

Figure 2.2: Schematic classification of energy saving components that access renewable energy sources

Energy saving building components that help buildings to make efficient use of fossil fuels are predominantly mechanical engineering components that relate to the heating, ventilation and air conditioning (HVAC) system. Typical energy saving building components in this category include cogeneration units, heat pumps, district heating, high-efficiency boilers, and building energy management systems.

There is much information on energy saving building components in the literature on the design of energy-efficient buildings. Overviews and annual reports like Lewis and Goulding (1994, 1999), provide listings of available energy saving building components, the manufacturers of these components, consultants operating in the field and tools that might be used to evaluate the performance of these components. Handbooks also give overviews of available components, describe properties of these components, give guidelines for building design, and sometimes formulas and tables to get a crude estimation of the performance of these energy saving building components. See for instance NOVEM (1992) or Goulding *et al.* (1993). Some energy saving building components are often used together, like for instance the use of aquifers, heat pumps and low temperature heating systems. As reported by ISSO (1999), the buildings with specific sets of energy saving building components can be classified accordingly, resulting in categories like high-tech, low-tech, smart-tech and eco-tech energy-efficient buildings. However, since the actual performance of an energy saving building component depends on the specific building design in which it is integrated and the context in which it operates, this literature is not able to provide designers with information that can be used to support a performance-based selection for a new specific building.

Many (architectural) journals, magazines and books describe energy-efficient buildings, often including a global overview of the design process resulting in this building design. However, since building design processes are long and complex, these descriptions never reach down to explicitly analyze the decision process that results in the selection of specific energy saving building components; at the most they list the main advantages that a selected energy saving building component has.
Finally, reports on specific building projects often contain detailed information about the performance of the building (either as designed or as built), which might be the result of calculations before construction or even on-site measurements after completion (as designed: e.g. Buis *et al.* (2000); as built: e.g. the TOBUS (2003) project). In these reports however only the final building design is evaluated; (public) reports that describe analysis of different building design variants with different energy saving building components are very rare. Studies from third parties, observing the activities of architects and consultants during the design of energy-efficient buildings that concern selection of energy saving building components, have not been found.

2.2.2. Building Energy Simulation Tools

There are currently many tools available for building energy analysis. These tools are often named building energy simulation tools[11]. In order to discuss the development of simulation tools over the years Clarke (2001, p.4) uses an evolutionary classification and distinguishes four generations of tools: a first generation, consisting mainly of manual methods based on analytical formulas and many simplifying assumptions (until the mid 1970s); a second generation with increased accountability for temporal aspects (mid 1970s – mid 1980s); a third generation based on numerical methods, which can be run on personal computers and allows for coupled simulation (mid 1980s – mid 1990s); and a fourth generation that adds program interoperability (mid 1990s – present). This classification clearly shows that the capabilities of building performance assessment tools increase with each new generation; unfortunately this also means that the complexity of these tools increases accordingly.

One of the best overviews of tools currently available is the building energy software tools directory provided by the US Department of Energy (2002a). This directory now lists more than 200 tools, ranging from software that is still under development to commercial software. The directory is organized in the following main categories: whole-building analysis, codes and standards, materials, components, equipment and systems, and other applications. A discussion of all these tools is not relevant for this thesis. However, to provide a background on tools that are named throughout the text a subset of the building energy tools that are suited for evaluation the energy performance of whole buildings is presented in Appendix B. The tools that make up this subset are the most frequently used and named energy simulation tools in current building energy simulation efforts and the corresponding literature.

Regarding future developments of building energy simulation tools, it is worthwhile to mention that a number of workshops organized by the US Departments of Energy and Defense (Crawley and Lawrie, 1997) set out to find out the requirements for a new generation of building energy simulation tools. These workshops confirmed that a better use of simulation programs for design is a wish of both tool developers and tool users. Yet the

[11] Strictly speaking energy simulation tools are only those energy analysis tools that actually reproduce the behavior (energy transfer) of buildings; however, in literature this distinction is not always made and many tools that assess energy-related building properties are simply named simulation tool as well.

overall findings regarding requirements for new tools did not reveal many unusual or new ideas; instead, integration with CAD systems, graphical input/output, use of default values, error checking, pre- and post-processing and better interfaces were identified as main points that needed improvement. Development of new tools and further development of existing tools continues since the mid 1990s, but without large breakthroughs.

Information on the role of simulation tools in the building design process proves to be hard to find. One study which focused on a qualitative assessment of the use of energy tools in the building design process by both architects and experts was carried out by Robinson (1996); however, quantitative information on the percentage of building projects that actually involves the use of building energy simulation tools so far is not available.

2.3. Integration of Building Performance Analysis Tools and Building Design

This paragraph discusses previous efforts to integrate building design process and building energy simulation, as well as ongoing efforts. In order to provide a context for the efforts within the building industry it starts with a brief discussion of integration of design and simulation in other disciplines.

2.3.1. Integration in Engineering Design

Outside the building industry, many other disciplines (especially those in the field of engineering), do integrate design and simulation. Good examples of this are the aerospace and automobile industries, and the domains of chemical plants and electronic circuit development. A good general overview of the field of engineering design is provided in (Birmingham *et al.*, 1997), treating its context, theories and practice.

In these other disciplines[12] application of simulation during the design process is common use. Many research projects have studied the design process in these engineering disciplines (this design process will subsequently be named engineering design process) and have tried to develop general models of this process. A good overview of some of these models is provided by Cross (2000) who describes the process models introduced by French, Archer, Pahl and Beitz, the VDI, March and his own model in some detail. Birmingham *et al.* (1997) describe the models of Hall, Darke, Lawson, March, Pahl and Beitz, Pugh and Cross. Van der Kroonenberg and Siers (1992) describe models by Hansen, Krick, Asimow, Rodenacker, Matousek, Roth, Koller as well as the VDI. As most authors indicate, no universally accepted model of the design process has emerged from these studies. Not surprisingly, none of the research-oriented models have encountered widespread acceptance by design practice, see e.g. (Birmingham *et al.*, 1997; Pahl *et al.* 1999; Shahidipour *et al.*, 2000; Austin *et al.*, 2001). Birmingham *et al.* (1997) also observe that there is a stark difference between models that

[12] When discussing integration of design and simulation in these other disciplines it is important to note that a number of factors set the discipline of building apart from these others. Eastman (1999, p.27) notes the following differences: the building industry applies a great range of possibly applicable different construction technologies, whereas other industries mostly have one dominant technology; in the building industry the ratio of design cost to product cost is higher than in any other industry, since it does not produce many large series of identical buildings; the building industry is probably unique in redesigning/modifying finished products on a large scale (adding rooms to buildings is usual; no one is adding extra doors to existing cars); and finally the building industry is made up of many small companies rather than a few large companies, working together in different teams and resulting in ever-changing communication patterns, making it difficult to develop new technologies in one firm, and making it more difficult to change the common practice.

have been developed for the engineering and architecture disciplines, although hybrid models that combine both disciplinary views are starting to appear. In general, engineering models are more linear, prescriptive and tree-like, having a well-defined sequence of stages, resting on exhaustive evaluation of requirements, and basically these models deal with a well-defined problem. The architectural process models tend to be more cyclical, descriptive and lattice-like, allowing for many process cycles; these models are mostly based on partly implicit and changing requirements and rely on tacit knowledge. Many design process models implicitly acknowledge the fact that design is an ill-defined problem.

The conclusion from these studies of design processes is that there is no such thing as one universal design process. Depending on the discipline there may be a sequence of main phases (similar to the main phases of the building design process that were presented earlier), but when it comes to the details within those phases there is bound to be a large diversity of approaches, sequences, etc. Therefore application of simulation tools in engineering design processes varies from domain to domain, and often even from project to project.

2.3.2. Earlier Integration Efforts

Efforts to integrate building simulation into the building design process have been undertaken from the moment that the field of building simulation emerged in the 1960s. As building simulation tools evolved and became more sophisticated, many attempts were made to make the new tools more accessible for building designers, resulting in a multitude of building energy design tools. Relatively few efforts took a tool-independent approach and studied integration from other viewpoints.

Tool-related integration efforts

Efforts that try to achieve integration of building simulation and the building design process through development of dedicated design tools are named tool-related integration efforts. In these efforts analysis of the reasons for lack of integration and development of solutions go hand in hand. According to Augenbroe (2001), these efforts have resulted in two categories of tools: tools that are intended for use by building designers/architects who are not experts in building simulation (tools for designers) and tools that are intended for use by design teams that include domain experts who are well versed in building simulation (tools for design teams with experts).

Tools for designers came into existence as soon as the first building simulation tools appeared. Knowledge generated with these simulation tools was made available to building designers through graphs and formulas that were based on computational results. Much of the results are presented in handbooks and design guidelines like Steemers and Baker (1994) and Blesgraaf (1996). Even today there are initiatives that try to disseminate information obtained from simulation efforts to architects (e.g. Mørk *et al.*, 1999). Other design guidelines have now been updated and have grown into computer programs for PCs (e.g. Baker and Yao, 2002).

When personal computers became widely available during the 1980s and made their way to the building design office, dedicated computer tools for building designers were created. These computer tools were based on state-of-the-art building simulation tools that were simplified/reduced to allow use of the tools by users that are no experts in the field of building simulation (Augenbroe, 2001). Many of these tools were based on simplified computational routines.

With the rapid advances in computer technology the simplified computational routines were overtaken by the possibility to hide the full complexity of advanced simulation tools from designers through the use of (graphical) user interfaces and the use of default values. A well-known recent effort is this field is Energy-10 (Balcomb, 1997). A tool that goes even further and tries to bring additional capabilities (described below for tools for design teams with experts) to designers is the Building Design Advisor (Papamichael, 1999). Other recent projects that aim to give architects direct access to simulation tools are presented by for instance van Dijk (2001) and Morbitzer (2003).[13]

Tools for design teams with experts focus on enabling the work of an expert user instead of relying on the use of interfaces and default values that hide complexity of simulation tools. This allows access to the full capabilities of the simulation tool(s). In this case the main challenge is to make sure this expert is provided with all the information that is needed to run simulations that are useful to the building designer. As the dominant use of computers by building designers is the use of computer aided design (CAD) systems as a graphics editor for creating building drawings, a lot of work has been invested in facilitating data exchange between these CAD-systems and building simulation tools (e.g. Bazjanac, 2001; Bauer *et al.*, 1998; Pelletret and Keilholz, 1999).

A further step is the development of building product models. Building product models are full digital building (design) representations that can be created, manipulated and analyzed using a set of computer tools. This not only allows for data exchange between a CAD-application and a simulation tool, but also for data exchange between different simulation tools, for instance energy, lighting and structural tools. A good overview of building product modeling is provided by Eastman (1999). Efforts in this field continue; ongoing projects will be discussed as state-of-the-art in integration in the next paragraph.

For the integration of building energy simulation and building design process one project had particular impact: the European COMBINE project. COMBINE (Computer Models for the Building Industry in Europe) had as goal to demonstrate the possibilities of an integrated environment for a number of state-of-the-art energy analysis and HVAC (heating, ventilation and air conditioning) tools. The project was carried out in two phases, both as part of European Union JOULE rational use of energy program.

- COMBINE 1 (1990-1992)
  The first phase of the project resulted in the development of a product model that was able to store building design information and allowed a number of building performance evaluation tools to share this data. This central product model was named the Integrated Data Model (IDM). The exchange of information between the IDM and the building performance evaluation tools was handled by tool-specific interfaces. A prototype was built in which the IDM was linked to six representative tools. As will be clear from this description, the first phase only addressed effective data exchange between tools (Augenbroe, 1994).

[13] This thesis will assume that it is important to support the decision of the design team, and that it is premature to presume that it is architects who should become users of simulation tools. As stated by Augenbroe (2001), there does not seem to be any apparent reason to remove the simulation expert or consultant from the design team. Instead, many recent building projects seem to go in the opposite direction and cannot be completed without the involvement of many different experts.

- COMBINE 2 (1992-1995)
  The second phase of the project addressed the use of the product model in an operational context. The IDM was extended and modified to allow more tools (including CAD) to be added to the system. During this phase the importance of capturing and managing the process in which tools are used became clear. In order to deal with this issue the concept of Project Windows was introduced. Project Windows are limited parts of the design process in which a number of pre-defined design operations can take place; in order to model Project Windows the process modeling technique of Petri Nets was used (Augenbroe, 1995).

Apart from the work on data exchange/product modeling, other developments in the field of tools for design teams with experts have investigated approaches in artificial intelligence and knowledge based systems. Important here are the intelligent integrated building design system IIBDS developed by ESRU (Clarke and Mac Randal, 1993; Clarke *et al.*, 1995) and the development of a Project Manager Application aiming at delivering simulation-based design decision support for use with ESP-r (Hand, 1998), both of which partly took place in the framework of COMBINE.
The work on the IIBDS contains two particularly interesting elements. One is the structure of an intelligent front end (IFE) that uses a communications module (blackboard) linked to a set of other modules that among others support a dialogue with the user, handle knowledge, keep track of performance goals, maintain building design information, and drive actual building performance assessment tools. Another is the work on the energy kernel system (EKS). The EKS provides for a combination of reusable models representing physical objects (parts of the building) and models representing abstract objects (performance prediction models and associated elements) in order to obtain a flexible simulation environment (Clarke and Maver, 1991).

MacRandal (1995) provides an interesting paper which has its roots in both COMBINE and the work at ESRU, which states very clearly that 'it is crucial for the uptake of simulation tools by the design profession that the process aspect of design support environments is given the study it deserves'. This paper stresses the process dimension, and point out the potential benefits of using process modeling and workflow techniques to enhance the integration of simulation tools and building design.

Work on presentation of simulation results must also be mentioned here. Especially the Integrated Performance View (IPV) developed by ESRU is a well-known example that combines graphical, visual and numerical data on different performance aspects in one standard format, allowing easy comparison of different design alternatives (Hand, 1998; Morbitzer, 2003; Prazeres and Clarke, 2003). However, there are many approaches to presenting simulation results, ranging from output in a specific format for architects (e.g. van Dijk, 2001) through the 'decision desktop' of the Building Design Advisor (Papamichael, 1999) to fully detailed numerical reports as provided by major simulation tools.

Tool-independent integration efforts
Of the integration efforts that do not concentrate on development of new tools a prominent project is the Energy Design Advice Scheme EDAS (McElroy *et al.*, 1997; Maver and McElroy, 1999), now continued in the Scottish Energy Systems Group SESG (Mc Elroy and Clarke, 1999, McElroy *et al.*, 2001; McElroy *et al.*, 2003). This project provides support in terms of access to the right expertise (as well as financial and material help), and allows building design teams to involve simulation experts and their tools in real design processes.

EDAS and SESG provide proof that intensive participation of simulation experts and their tools in design indeed solves the integration problem. However, this approach cannot be used for daily practice, as normal situations do not allow design teams to make such close use of experts.

Another project that demonstrated the feasibility of integration of building simulation and building design process is IEA Task 13: Advanced Solar Low Energy Buildings (Hestnes, 1997). The main objective of this task was to identify, develop and test new and innovative concepts to reduce energy consumptions in houses; the integration of simulation and the design process of these houses was demonstrated, albeit in a research context. A number of smaller projects (e.g. Kabele *et al.*, 1999; Shaviv, 1999; Hensen *et al.*, 2000; Lam *et al.*, 2001; Bartak *et al.*, 2001; McDougall and Hand, 2003) present similar findings.

Robinson (1996) explored a number of qualitative aspects of the use of building energy tools in design practice (both by architects and engineers) through a survey. One interesting issue is that Robinson questions the often expressed belief that simplified simulation tools are suitable for early design phases, whereas more complex tools are better for later phases. In contradiction to this common belief Robinson's results indicate that both simplified and advanced tools are used in similar phases, a viewpoint endorsed by Mahdavi (1999).

Work on the reliability of computational results obtained from building simulation tools must also be mentioned (e.g. Lomas *et al.*, 1991; Bunn, 1995; Palomo Del Barrio and Guyon, 2003). Although this research is mostly concerned with the quality of the tools themselves, it has been found that the reliability of the results obtained from simulation depends on both the simulation tool as well as the user of these tools. This is of importance for all efforts that aim to integrate building simulation into the building design process, whether those efforts focus on tools for designers (e.g. user interfaces), tools for design teams with experts (e.g. product models) or take a tool-independent approach.
Regarding implementable knowledge, the International Energy Agency has developed BESTEST, an approach that allows to validate and compare building energy simulation tools (Judkoff and Neymark, 1995). Complementing BESTEST are Performance Assessment Methods (PAMs). PAMs have been developed to provide guidelines for the users of the building energy simulation tools that help those users to input correct information to those tools. It is hoped that the use of PAMs minimizes differences in user interpretations (Wijsman, 1998).

Finally, it is important to mention that the use of simulation tools (whether tools for designers or tools for design teams with experts) can be complemented by automatic generation of building design variants (for instance by so-called genetic algorithms (e.g. Caldas, 2002) and a whole host of optimization and decision methods (e.g. French, 1993; Keeney and Raiffa, 1993; Cross, 1994).

Findings of earlier efforts
Although these earlier efforts to integrate building simulation into the building design process have not resulted in a final answer to the problem, the literature describing these efforts provides a number of plausible barriers to the integration of design and simulation in actual building design projects:

- Unavailability of appropriate computational tools or models.
  When addressing design problems availability of simulation tools and models can be problematic. Even if an appropriate tool or model exists it can be very difficult to find, as detailed information about tools and models (underlying hypotheses, applicability range) is seldom available (Pelletret *et al.*, 1995). Many tools can be used by their authors, but time and resource constraints result in a limited scope and limited facilities. Moreover, in spite of the work on building product models, many of these tools still do not communicate or share data with other systems (Hensen *et al.*, 1993).

- Lack of trust in computational results, possibly in connection with lack of usefulness and clarity of these results in a design context.
  While developers or distributors of computational tools may have confidence in their product, potential customers (especially architects and principals) often lack this confidence (Batty and Swann, 1997). For people that are no expert in simulation there is no independent measure, no benchmark to legitimize the output of these tools (Donn, 1999). Many computational tools lack information about their domain of use and their accuracy; often, objective information about the quality of underlying models is lacking (Pelletret *et al.*, 1995; André *et al.*, 1999). Moreover, if people who are not an expert in simulation do not have a concept of what outcome to expect, they will be reluctant to use or commission simulation (McElroy and Clarke, 1999). Even if a 'perfect' model would be available, there might still be different ways of interpreting the results (Mahdavi, 2003). In all cases, results must be meaningful to persons who may not be specialists in energy simulation or similar analysis work (Radford, 1993).
  Degelman and Huang (1993) even suggest that computational results should be presented in graphical formats, which might be more close to the way building designers communicate during the design process. Herkel *et al.* (1999) argue that it is desirable to present feedback of thermal simulation in the three-dimensional context of the building.

- High level of expertise needed to utilize building simulation tools.
  In order to effectively use building simulation tools users must know which building features affect predicted building performance and hence need to be included in the building model. They must know how to evaluate and verify simulation results (Donn, 1999). Building designers have practical knowledge but are seldom educated in building simulation. They can be expected to give a detailed description of an envelope construction, but not all are able to select a suitable convection coefficient (Haltrecht *et al.*, 1999). As most companies that design buildings do not have the means to employ simulation specialists, simulation tends to remain an expertise procured from (external) consultants (McElroy *et al.*, 1997).

- Costs (time and money) connected with building simulation efforts.
  Many researchers state that there is not enough time and money available for use of simulation tools during the building design process, and that professionals in building practice still need to be convinced that increasing the duration and costs of the design phase pays off during building construction and operation (Aho, 1995), (Pelletret *et al.*, 1995), (McElroy *et al.*, 1997), (Tabary, 1997), (Bazjanac and Crawley, 1999), (Hand *et al.*, 1999), (Donn, 1999). Lam *et al.* (1999) note that this effect is enhanced by the trend of leasing out buildings, that sees buildings not being occupied by their owners.

- Problems related to data exchange between 'design' and 'simulation'.
  Managing the information exchange (from design drawing to input, from one tool to another, etcetera) is an important bottleneck in applying simulation tools within the building design process (André *et al.*, 1999). In many cases building simulation early in the design process requires informed guessing by the simulation expert because crucial information is not yet available; this information just cannot be provided by the design in this stage, resulting in the need to use default values (Karola *et al.*, 1999). After the analysis is performed the design might be developed to a level that does contain this defaulted information, resulting in questioning of the computational results (Bazjanac and Crawley, 1999). Tabary (1997) suggests that this characteristic of the design process requires tools that are based on a gradual approach, allowing to start evaluating with only little information and moving on to a higher level of detail as more information becomes available. McElroy and Clarke (1999) observe that data exchange needs to be complemented by exchange of purposes: 'because modeling specialists are not building designers, and building designers are not (yet) proficient modelers, the mapping of design question to modeling intent is a non-trivial activity'.

2.3.3. State-of-the-art in Integration

Most ongoing efforts on integration of building simulation and building design process take place in the category of tools for design teams with experts. Augenbroe (2001) identifies four major approaches towards integration, which he expects to develop and possibly merge in the future:

1. *automated data transfer*
   This approach assumes that the integration problem is mainly a problem of information exchange between a) building designers and their tools and b) building simulation experts and their tools. It tries to solve this problem through the development of one shared building model (product model) which can be accessed by all tools, resulting in interoperability of these tools. The COMBINE-project discussed in the previous paragraph explored this approach; currently efforts in this direction are coordinated by the development of the International Alliance for Interoperability Industry Foundation Classes IAI-IFC (Bazjanac and Crawley, 1999; International Alliance for Interoperability, 2002; Bazjanac, 2003). See figure 2.3a.

2. *consultant taking care of integration*
   This approach solves the integration by including simulation experts and their tools in the design team and ensuring sufficient interaction between designers and simulation expert takes place. The main projects taking this direction, EDAS/SESG, was presented in the previous paragraph (Maver and McElroy, 1999; Mc Elroy and Clarke, 1999; McElroy *et al.*, 2003). See figure 2.3b.

3. *re-development of simulation tools to circumvent the integration problem*
   This approach aims to redefine interoperability from a functional and behavioral viewpoint, basically by developing new modular simulation tools that are geared towards communication with the building design team. The main project in this direction is SEMPER, a multi-aspect prototype design environment developed by Carnegie Mellon University. SEMPER provides on-line feed-back on a set of performance aspects in order to help with exploration and understanding of the interaction between various design and performance variables. SEMPER consists of a shared object model (SOM) which is

dynamically linked to domain object models (DOMs) within the various simulation modules. SEMPER envisions to deliver additional design support by introducing bi-directional inference between building performance and design. This means that the system shows the effect of changing a design variable on the resulting building performance, but also indicates which design variables need to be changed in order to obtain a specified change in building performance. A general overview of SEMPER is provided by Madhavi (1999); a discussion of the product models is given by Mahdavi *et al.* (2002). Recent implementations are described in (Madhavi, 2001).
An internet-based version of SEMPER named S2 was developed to demonstrate how the system can be adapted to support collaboration between different users working at different geographical locations (Mahdavi *et al.*, 1999; Lam *et al.*, 2003). However, SEMPER as well as the re-definition approach are still under development. See figure 2.3c.

4. *minimalistic data-transfer through process-context sensitive, light-weight interfaces*
   This approach supposes that automated data exchange only makes sense if the process context in which simulation takes place is taken into account. Since all simulations have a purpose to analyze building performance, full interoperability in which all data is accessible for all tools results in excessively complex interfaces and redundant data transport between building product model and tools. The solution for this is believed to be capturing of the process context in scenarios in which analysis efforts can be embedded. In this process context a minimalistic interface to a suitable simulation tool will be provided for each analysis task. An example of work in this category is the Design Analysis Interface - Initiative (Augenbroe and de Wilde, 2003); part of the work in this thesis is closely related to this project, see chapter six. See figure 2.3d.

Note that none of these state-of-the-art approaches appears to fully address all the barriers to integration of building design process and building simulation as identified from earlier efforts:

- automated data transfer does not solve the problems of lack of trust in computational results, and assumes (so far without proof) that one universal model can be developed that can be used to analyze all building designs;
- consultants taking care of integration still need to find suitable tools and models, and have to operate those within the available time and money;
- re-development of simulation tools will still have to deal with the problem of having sufficient expertise in the design team, as well as getting the team to trust in results, in order to be successful;
- minimalistic data-transfer still has to build the same trust in the results, whereas it probably requires another kind of expertise (process modeling related).

In the meantime design teams must do the best they can using available tools and methods.

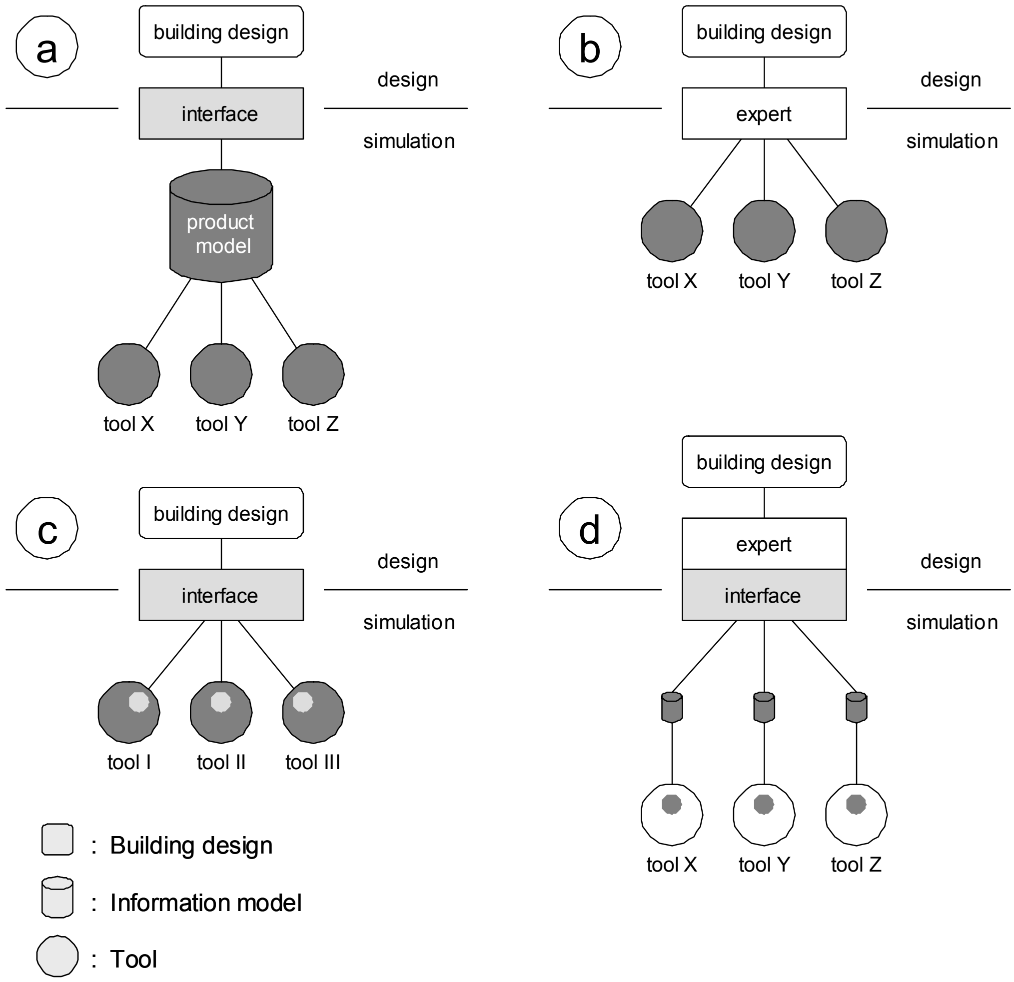

Figure 2.3: Different state-of-the-art approaches to integration of building design and building simulation

2.4. Discussion and Conclusion

This paragraph summarizes the most important findings of the overview of previous work in the field of integration of building simulation and building design process as presented in this chapter. Based on this overview it will identify unsolved problem areas as well as starting points for the research presented in this thesis.

2.4.1. Summary

In this chapter three main issues have been addressed: building design, energy-efficient buildings, and integration of building design process and building simulation.

The section on building design discusses relevant aspects of the building design process, increasing quality demands (or performance requirements) for buildings, and building performance simulation as an important option to guarantee that buildings indeed meet the increasing quality demands. It identifies the following relevant issues:

- The building design process continues to change, due to ongoing specialization of the actors and due to the introduction of new, innovative technologies.

- In building requirements a trend towards increasingly stringent, performance-based building codes and rating systems is identified, resulting in an increasing need for building performance assessment.
- Building (performance) simulation is the domain of simulation that studies the behavior of buildings or building sub-systems. The most relevant behavioral aspects studied in building simulation are heat transfer, (day)lighting, acoustics, and air flow.
- The following main trends in building simulation have been identified: continuous efforts in the field of tool interoperability, development of modular tools, work on coupled field simulation, an increased impact of the internet, and continuous work on a number of other issues (like validation, error diagnostics, sensitivity, uncertainty and risk analysis, standard post-processing, animation etc.)

The section on energy-efficient buildings focuses on attaining the specific goal of designing buildings that are energy-efficient. The use of energy saving building components as well as the use of building energy simulation tools in achieving this goal are discussed. The following issues are put forward:

- The use of specific energy saving building components is rising. The following main categories of energy saving building components can be identified: energy saving building components that minimize the energy needed by buildings, energy saving building components that access renewable energy, and energy saving building components that help buildings to make efficient use of fossil fuels.
- There is a lack of information that helps building design teams to make a performance-based selection of energy saving building components for new buildings. Moreover, it is found that there actually are no unbiased studies that describe how the selection of energy saving building components takes place in current building projects, and whether (and how) building energy simulation tools are used to support this selection.
- Regarding the use of building energy analysis tools to support the design of energy-efficient buildings, there currently are many tools available for building energy analysis. Yet information on the actual role of simulation tools in building design proves to be hard to find; quantitative information on the percentage of building projects that actually involves building energy simulation so far is not available.

The section on integration of building design and building simulation provides an overview of integration in other engineering design disciplines, followed by a discussion of earlier efforts and the state-of-the-art in integration in the building industry. The following main issues are important:

- Regarding earlier efforts to integrate building simulation and building design process a large number of tool-related integration efforts has been identified; the tools resulting from these efforts can be divided in tools for designers (to be used by building designers only) and tools for design teams with experts (tools that are assuming use by simulation experts). Also a number of tool-independent integration efforts has been identified.
- The earlier integration efforts have identified a number of plausible barriers to the integration of building simulation and building design process:
    - unavailability of appropriate computational tools or models;
    - lack of trust in computational results, possibly in connection with lack of usefulness and clarity of these results in a design context;
    - high level of expertise needed to fully utilize building simulation tools;
    - costs (time and money) connected with building simulation efforts;
    - problems related to data exchange between ‘design’ and ‘simulation’.

- The following approaches towards integration of building simulation and building design process are considered to represent the state-of-the-art:
  - automated data transfer;
  - consultant taking care of integration;
  - re-development of simulation tools to circumvent the problem;
  - minimalistic data-transfer through process-context sensitive, light-weight interfaces.

  Yet these state-of-the-art approaches towards integration are all based on a technology-push approach; none of them seems to address the whole set of barriers to integration of building design process and building simulation as identified from earlier efforts.

2.4.2. Conclusions

The overview of previous work in the field of integration of building simulation and building design process leads to the following conclusions:

1. New, innovative technologies and components on which no or only little experience is available are employed in buildings.
2. Buildings have to meet increasingly stringent quality demands. In order to guarantee that buildings indeed meet these demands, an increased use of monitoring of building performance, experimental set-ups and computational tools is required to enable performance-based building design decision-making.
3. Many of the earlier integration efforts are biased by their up-front commitment to the development of a specific tool, limiting their contribution to the whole field. In a related issue, the earlier efforts also lack a hard analysis of the role of existing tools in current practice.
4. There are no unbiased studies available that describe how the selection of energy saving building components takes place in current building projects, and how building energy simulation tools are used to support this selection. Neither is there any quantitative information on the uptake of building energy simulation tools in current design practice.
5. Integration of building simulation and the building design process still has to overcome the barriers of unavailability of appropriate computational tools or models, lack of trust in computational results, the high level of expertise needed to fully utilize building simulation tools, the issue of costs (time and money), and the problems related to data exchange between 'design' and 'simulation'.
6. The development of new building energy simulation tools shows a continuous increase of capabilities and complexity. This trend seems to increase the barriers to integration of building design process and building simulation even further.
7. Ongoing efforts to integrate building simulation and building design process mostly seem to take a technology-push approach, and do not seem to address all barriers to integration identified by earlier efforts.

2.5. Research Questions

Based on these findings the following research questions have been identified as being essential for achieving the overall goal of this research project - the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components:

1. What is the current way of selecting energy saving building components during the design of energy-efficient building projects, and how adequate is this?

2. To what extend are existing building energy simulation tools used during the selection of energy saving building components, and to what end? How adequate are these existing tools?
3. How can the current way of selecting energy saving building components be improved?
4. How can existing building energy simulation tools be improved? And what effect can be expected from ongoing developments and integration efforts?
5. How can improvements of the way of selecting energy saving building components and improvements on the part of tools be combined into a strategy to provide computational support for the selection of energy saving building components?
6. Can a prototype be developed that demonstrates how the proposed changes actually lead to better integration of design and simulation, and hence to improved computational support for design decisions with respect to the selection of energy saving building components?

3. Analysis of Current Energy-efficient Building Design Projects

"We were both looking at the same thing, seeing the same thing, talking about the same thing, thinking about the same thing, except he was looking, seeing, talking and thinking from a completely different dimension."

(Robert M. Pirsig)

The overview of previous work presented in the previous chapter concluded that many of the earlier efforts on integration of building design process and building simulation lack a profound analysis of the role of existing tools in current building design practice. It also concluded that there currently are no unbiased studies available that describe how the selection of energy saving building components takes place in current (completed or ongoing) building projects, and how building energy simulation tools are used to support this selection. The goal of this chapter is to fill in this gap by answering the following two research questions:

- What is the current way of selecting energy saving building components during the design of energy-efficient building projects, and how adequate is this?
- To what extend are existing building energy simulation tools used during the selection of energy saving building components, and to what end? How adequate are these existing tools?

In order to achieve this goal this chapter analyses real, prestigious contemporary building projects in the Netherlands[14]. The decision to analyze building projects in the Netherlands was made because of easy access to information and design team members. For these projects current practice regarding selection energy building components, including the use of computational tools, is analyzed (de Wilde *et al.*, 1999a; de Wilde *et al.*, 1999b; de Wilde *et al.*, 2001a). The research methods employed in the chapter are case-studies and a survey. Throughout the chapter the standard classification of the design process in five main phases[15] has been used, in order to ensure maximal comparability of the results of both the case-studies and the survey.

The chapter starts in paragraph 3.1 with an analysis of different aspects of current energy-efficient building projects in order to obtain detailed research questions. This is followed in paragraph 3.2 by an overview of available methodologies for the study of design practice, which provides a background for the approach of the research presented in this chapter: case-studies and a case-study related survey. Paragraph 3.3 describes three case-studies that have been conducted to gather in-depth information on the selection of energy saving building components and the use of computational tools, and how comparison of the cases provides a general view of current practice. Paragraph 3.4 describes a survey that was conducted to verify whether or not the results of the case studies hold for a larger sample, and to gain additional insights. Paragraph 3.5 closes the chapter with discussion and conclusions.

[14] In overviews of application of energy saving measures in the building industry (e.g. van Hal, 2000) the Netherlands rank among the top quarter of European countries regarding the use of energy saving measures.

[15] The phases are: feasibility study, conceptual design, preliminary design, final design, and preparation of building specifications and construction drawings. This classification is described in detail in paragraph 2.1.1. on the building design process; it is in general use in the building industry.

3.1. Current Energy-efficient Building Design Projects

In current energy-efficient building design projects many aspects can be expected to influence the way energy saving building components are selected, and the way tools support that selection. There can be different reasons for the decision to select (and subsequently integrate) energy saving components: the immediate cause might be the brief presented by the principal, ambitions of the architect, legal requirements, or an interest of the design team to experiment with a specific component. On a different level, the design team can select energy saving building components to obtain specific results, like a reduction of the heating load, cooling load or energy consumption related to artificial lighting. The decision to select a specific component can be expected to be influenced by other performance aspects as well, and especially by the expected thermal comfort in the building.
Assessment of the performance of the combination of building and component(s) is paramount in making deliberate decisions on selection of energy saving building components. For this assessment many different computational tools can be used, all having their own advantages and disadvantages. A suitable tool must be chosen. Yet even for a suitable tool it is important to note that the usability of computational results still depends on the way the building and component(s), physical transport and boundary conditions are modeled, and translated to input for that tool.
From a design process point of view it is imperative that the choice of energy saving building components and the use of computational tools to support that selection take place in the same phase of the design process; if there is no synchronism there can be no useful interaction[16].
Finally, in real design projects selection of energy saving building components and the use of computational tools will take place in a dynamic environment. This provides a complex context that must be considered when analyzing the selection of energy saving building components and the use of tools, since different actors, design team structures, handbooks, data on demonstration projects and experience gained in evaluated or monitored projects might have an impact, too.

Within this complex context, this chapter aims to analyze the current way of selecting energy saving building components during the design of energy-efficient building projects, and the extend and contribution of the use of existing building energy simulation tools. This will be realized by the answering of the following detailed research questions for a set of prestigious energy-efficient projects in the Netherlands:

1. Is there synchronism between the selection of energy saving building components and the use of computational tools?
2. How does the selection of energy saving building components take place?
    - What aspects are considered in the selection?
    - What is the role of performance requirements?
    - How is performance predicted? (Which performance aspects have been assessed? Which combinations of building and component(s) have been evaluated? And what instruments or tools have been used for the prediction?)

[16] Note that this is different when it comes to verifying a choice; in that case the choice may precede the use of tools.

3. Are tools being used to support this selection? If so, how do they impact the decision?
    - What type of tools is used, and why?
    - How do these tools influence the selection?
    - What can be said about the suitability of these tools for assessing this building?
4. What other factors influence the selection of energy saving building components and the support provided by tools for this selection?

3.2. Selection of Empirical Research Methods

There are several approaches for empirical research in design, applicable to both architectural and engineering design processes. The object of the study can either be a real-life design process in practice / industry or an artificial design process in a laboratory experiment (often in the form of workshops). Study of real-life design processes (e.g. Badke-Schaub and Frankenberger, 1999; Emmitt, 2001) requires an enormous effort to gather data, as design processes can take a long time and can be very complex; on the other hand this allows to observe design taking place in situ, embedded in the organizational and social frameworks that provide its context (Pahl *et al.* 1999). An additional problem for ongoing design projects is that it is not always possible to predict the result: very different designs might meet the same criteria, and a design project might be unsuccessful (for instance if the principal decides to go for a competing project). Artificial design processes or workshops (e.g. Macmillan *et al.*, 2000; Austin *et al.*, 2001) allow to focus the research, by only studying an aspect or part of the design process, comparing different teams working on the same problem, etc. However, this comes at the costs of loosing the context that is encountered in real design processes. Observation of the design process can take place directly or indirectly. In direct observation a non-participating person records the ongoing design process; in indirect observations the actors in the design process themselves provide information on that process by means of interviews, diary sheets or questionnaires. Direct observation always takes place during the design process. Indirect observation can take place both during the design process (actors taking notes) and after the process has been completed (interviews, questionnaires). Of course the different methods can also be combined. However, as observed by (Pahl *et al.* 1999), the entrance to the internal thoughts of the members of the design team always remains limited.

The objective of this chapter is to analyze real building design projects in order to find out in which way energy saving building components are selected, and how tools support that selection. In order to meet this objective the following approach has been followed:

- Research methodology considers case-studies to be an appropriate method for obtaining qualitative information on processes or objects, allowing open observation of the subject (e.g. Verschuren and Doorewaard, 1995). Therefore a number of cases (3) have been explored; the findings of these cases have been subject of a cross-case analysis.
  The choice has been made to do a retrospective analysis of a number of prestigious energy-efficient buildings in the Netherlands. This allows to study long-term design processes (often taking more than a full year) in a relatively short period, while focusing on points of interest in those processes. As a consequence, the observation method had to be indirect, relying for information on the actors that were involved in the design processes.
- Research methodology considers surveys to be an appropriate method for obtaining quantitative data on processes or objects (e.g. Verschuren and Doorewaard, 1995). In order to verify the representativeness of the three cases for prestigious energy-efficient

projects in general, and to obtain quantitative data, a case-study related survey has been conducted.

3.3. Case Studies

The design processes of three recently completed buildings have been analyzed in order to study decisions concerning energy saving building components and the role of computational tools in current building design practice. The objectives of the case-studies were as follows:

- obtain insight in the mechanisms/techniques used for the selection of energy saving building components during the building design process;
- obtain insight in the use of computational tools in relation to the selection of energy saving building components.

Note that study of the design process of these cases in general was not an objective; this would have made the scope of the work unnecessary broad. After studying the cases separately a cross-case analysis has been carried out to provide a general view on selection of energy saving building components and use of computational tools in current building design practice.

The cases investigated have been selected based on the following requirements:

1. emphasis on the deployment of energy saving building components;
2. use of simulation tools during the design process;
3. willingness of design team and consultants to participate in the research project.

Furthermore, the cases have been selected from a narrowly defined class of project types and size as to have enough similarity among them to warrant general conclusions about characteristics of the design process and design decisions. Large office building projects with a high energy saving profile have been selected, because these projects are the most likely to involve the use of energy saving building components as well as the use of simulation tools during the design process. For similarity in size, cases with a floor area of approximately 10.000 m^2 have been selected.

The design processes of the following office buildings have been analyzed:

1. Rijnland Office
2. ECN Building 42
3. Dynamic Office.

Rijnland Office, Leiden

- architect: Jan Brouwer Associates, Den Haag
- consultant: Halmos BV, Den Haag

This building has been designed to become the headquarters of the Rijnland Regional Water Authority in Leiden. Gross floor area is 12.000 m^2, the building accommodates +/- 300 people. The Rijnland brief asked for an environmentally conscious building. This has resulted in a number of energy saving measures, including use of the following energy saving building components: long term energy storage in the soil, heat pumps, low-temperature heating, high temperature cooling, heat exchangers, climate facade, daylighting systems, atrium. Also attention has been paid to careful selection of building materials, and a rainwater reuse system has been added as well. The building was completed in 1999. See figure 3.1.

Figure 3.1: Rijnland Office, Leiden

The project has been granted the status of exemplary project in the field of energy-conscious and sustainable building by the Dutch government through SEV (Steering Committee for Experiments in Public Housing) and NOVEM (Netherlands Agency for Energy and the Environment).

ECN Building 42, Petten

- architect: BEAR Architects, Gouda
- consultant: ECN Unit Renewable Energy in the Built Environment, Petten

Building 42 is a new building for the Energy research Centre of the Netherlands (ECN), and was built to increase office and laboratory space available. According to the ECN mission, the new building should ‘contribute to a clean and reliable energy supply for a viable world’. See figure 3.2.

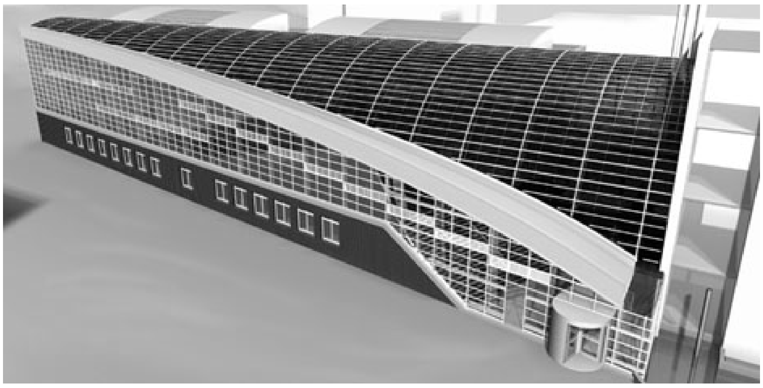

Figure 3.2: ECN Building 42, Petten

The master plan for Building 42 consists of three identical units, interconnected by a large conservatory that also connects to the existing Building 31. Gross floor area of Building 42 is about 9.000 m^2 in total for the three units. The first unit of the building was completed in 2001. The following energy saving building components have been integrated into the design of Building 42: photovoltaic arrays, conservatory, daylighting systems, atria, co-generation unit, heat exchangers, and a nocturnal ventilation system (for cooling in summer).

Dynamic Office, Haarlem

- architect: Uytenhaak, Amsterdam
- consultant: Sweegers en de Bruijn, ‘s Hertogenbosch

The Dynamic Office is a building that has been realized on a highly complex building site near the Haarlem railway station. See figure 3.3.

Figure 3.3: Dynamic Office, Haarlem

Gross floor area is 8.900 m^2; apart from offices the building accommodates some shops and a part of the railway station itself. An innovative feature introduced in the Dynamic Office is the concept of variable working spaces, which allows a more efficient use of available office space. Furthermore, the following energy saving building components have been integrated into the building: atria, a façade which provides sunshading by means of overhangs, thermal mass (resulting in redundancy of a cooling machine), energy-efficient lighting and energy-efficient computers. The Dynamic Office was completed in 1997.

Remark:

The search for potential cases proved to be hard. Based on a list of energy-efficient buildings architects and consultants were asked to participate in the research; however, a considerable number of candidates was not prepared to collaborate in this project. Mostly the motivation for refusal was lack of time; however, in some cases it was clear that participants in a design process passed the responsibility around. This gave the feeling that some design teams did not want to have the design process of their energy-efficient building analyzed. From this point of view the participants in the case studies must be appreciated for coming out into the open. One can also infer that the architects and consultants collaborating in this project had a lot of confidence in their designs.

3.3.1. Approach

Each case has been analyzed using the following approach:

1. Data gathering phase:

Phase one consisted of collecting relevant information about the case. Literature concerning the case was reviewed. Participating companies, key actors within these companies, their disciplines and the teams and structures in which they operated were identified and laid down. Special attention was paid to communication patterns and reports of team-meetings. Finally the most important participants in the design process (the architect and the simulation expert) were interviewed, using personal (face-to-face) interviews. The interviews were focused on selection of energy saving building components and use of computational tools during the design process. They were conducted by the author of this thesis in accordance with the general rules for interviews as described in e.g. Brenner *et al.* (1985) and Trochim (2002)[17].

The interviews started with the request to describe the design process of the case in general. Thereupon the participants were asked to position all relevant decisions regarding energy saving building components in that description of the process, as well of the use of computational tools. Then all decision moments concerning energy saving building components, with or without the intervention of expert analysis, whether supported by the use of computational tools or not, were discussed in depth.

2. Process modeling phase:

Phase two consisted of a structured analysis of the data collected in phase one. The design process of the case, and especially the activities within that processes that deal with energy saving building components or the use of computational tools, was represented formally by means of process models according to the IDEF-0 process-modeling method (Hunt, 1996; Knowledge Based Systems Inc., 2002). IDEF-0 was selected as process modeling method for the case-studies because it provides a good overview of the overall process, results in formalized diagrams, and because several tools supporting IDEF-0 modeling and visualization are available. Clearly the main focusing point within the final process diagrams should be the selection of energy saving building components and use of simulation tools within the design process. For the translation of the raw data of the interviews into process models a common listing (repository) with all process elements was used. By scanning this listing for existing similar elements before defining new ones the number of elements was limited. This maximal similarity guarantees optimal comparability between the final process models.

IDEF-0 (Integral Definition) models are designed to help promote good communication about processes and to help the process analyst in identifying what functions are performed by the process, what is needed to perform those functions, what the process does right and what the process does wrong.

IDEF-0 models represent a process as a series of diagrams. In these diagrams the activities that make up the process are depicted as boxes. Interfaces between the activities are depicted as lines with arrows that either enter or exit an activity box. Four kinds of interfaces (called concepts in IDEF-0) are distinguished:

[17] A general procedure for conducting interviews consists of explanation of the context of the interview, use of a questionnaire with written questions, use and adherence to a pre-defined order of questions, asking of all questions, use of probing techniques, immediate recording of responses, and a formal conclusions of the interview

- inputs: information or objects required to perform the activity;
- outputs: information or objects that are created when the function is performed;
- controls: the conditions or circumstances that govern the activity's performance;
- mechanisms: the persons or devices that carry out the activity.

Inputs enter activities from the left, controls from the top, mechanisms from the bottom. Outputs leave activities on the right. See figure 3.4.

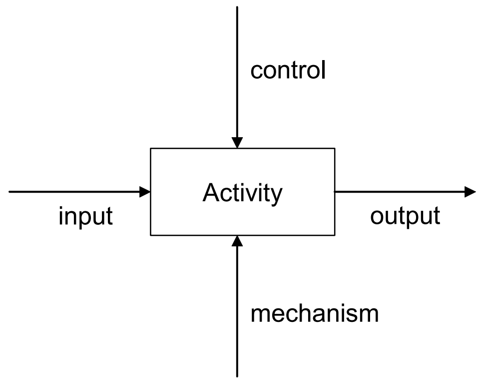

Figure 3.4: IDEF-0 representation of concepts and activities

IDEF-0 uses a hierarchy of diagrams. One top-level diagram (A0) shows the process as one activity only; this activity is broken down (decomposed) into more detailed diagrams (A1, A2, A3) that can themselves be decomposed until the tasks are described at a level necessary to support the goal of the process model. See figure 3.5.

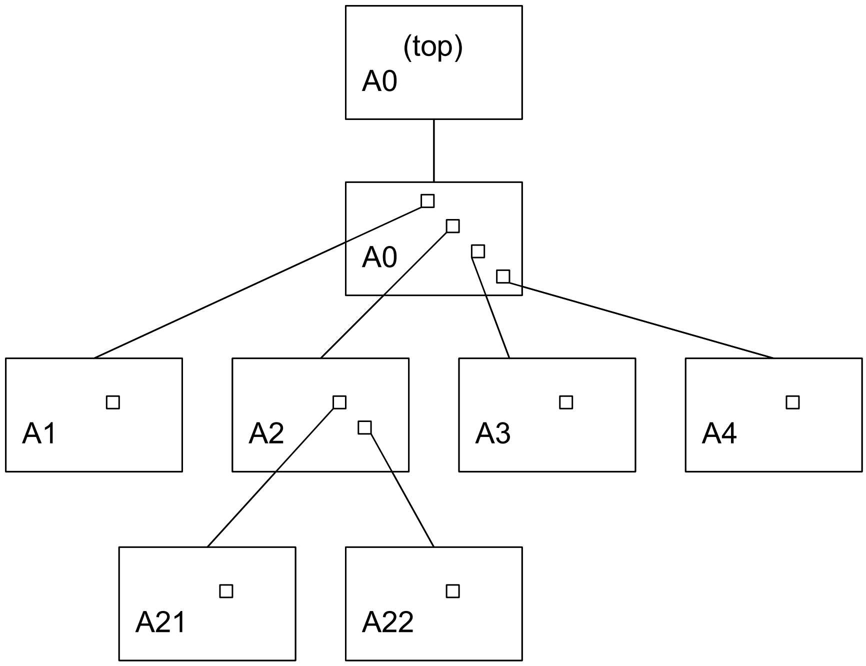

Figure 3.5: Structure and naming of IDEF-0 decomposition diagrams

For an efficient implementation of IDEF-0 the KBSI function modeling tool AI0-WIN has been used to support the process modeling of the cases (Knowledge Based Systems Inc., 1996).

It is important to note that IDEF-0 process models do not include representation of the factor time. The only relation between activities are input-output relations. Though most models for convenience will start with the first activity in the upper left corner and the last activity in the lower right corner, a model could just as well be made the other way around. See figure 3.6. In the process models of the case-studies an implicit ink between the time axis and the activities in the model is made by coupling of the design phases through clearly defined products, for instance the activity of conceptual design resulting in a conceptual building design drawings, which is the input for the activity of preliminary design (Hunt, 1996; Knowledge Based Systems Inc., 2002).

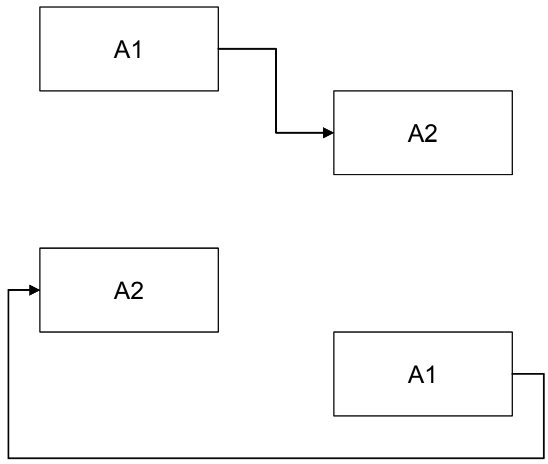

Figure 3.6: Equivalent IDEF-0 diagrams, showing that IDEF-0 do not represent time

3. Feedback interaction phase:
In phase three a second interview with the architect and the simulation expert was used to obtain feedback and to have errors or oversights that might be present in the models corrected. In this interview the key actors (process experts in 'design' and 'simulation') consulted in phase one were asked to review the process models resulting from phase two. During this second interview the experts were also asked to suggest possibilities for improvement of the design process (with regard to the selection of energy saving building components and use of computational tools).

4. Cross-case analysis:
The analysis of individual cases was followed by the cross-case analysis. Here the occurrence of similar activities and concepts in the three process models was studied to define a general process model representing the common findings of the three cases, that can be used to describe general practice in current building design projects.

The results obtained from the individual case studies are presented in the paragraphs 3.3.2. 3.3.3. and 3.3.4. Each case is presented in the same format. First, the background of the selection of energy saving building components in the project is discussed, taking a look at the relation with the brief, the initiator of the selection, and the goal of selection of these components (A). Next comes a description of the procedure that was followed in selecting the energy saving building components, including (where applicable) a discussion of the role of performance requirements and other performance aspects that impacted the selection (B). Finally, the synchronism of the selection of energy saving building components and use of tools, the type of tools that has been used and, where possible, the suitability of these tools for use in this specific design context will be reviewed. The interested reader is referred to appendix C for the full IDEF-0 process models and description in text of the design processes of the three cases. The cross-case analysis is presented in paragraph 3.3.5.

3.3.2. Rijnland Office, Leiden

A - Background of the selection of energy saving building components

The brief for the design of the Rijnland Office only provides general instructions, requiring the design to be environmentally friendly. The further elaboration of this term is left to the design team.

The decision to make the building energy-efficient is initiated by the architect, who considers energy efficiency to be a part of the broader objective of designing an environmentally friendly building. To realize an energy-efficient building the architect invites an expert consultant for HVAC systems into the design team.

The goal of introduction of the energy saving building components into the design of the Rijnland Office is to obtain a building that is more energy-efficient than standard offices. However, no specific target or goal is specified.

B - Procedure for the selection of energy saving building components

Most of the energy saving building components of the Rijnland Office (long term energy storage, heat pumps, low-temperature heating, high-temperature cooling, heat exchangers, climate façade, atrium) are selected during the phase of conceptual design. These components are suggested by the consultant, who has used the same components in previous projects. The components are mostly HVAC-components that have little impact on the architectural design, thereby allowing the building design process to be separate from the HVAC-system design.

The daylighting system is selected in the later phase of final design. In this case, different options (window arrangement, types of blinds, translucent insulation material, reflective ceiling) are considered. Their impact on daylight access is simulated using the lighting simulation tool Radiance, while visual comfort and aesthetics are assessed using experimental set-ups. The final selection is made by the principal, based on visiting the set-up and rejecting the reflective ceiling because of visual disturbance; the next-optimal combination from a daylighting point of view (blinds) is selected.

Specific performance requirements by the principal do not impact the selection of energy saving building components. However, the early integration of a whole set of these energy saving components makes it easy for the design to meet the legal energy efficiency requirements in a later phase.

The low-temperature heating and high-temperature cooling are bound to have some impact on thermal comfort, yet this is not quantified; the feasibility of these components is accepted based on the earlier use of these systems by the consultant.

C - Role of computational tools in the selection of energy saving building components

The crucial phase for the integration of energy saving building components into the design of the Rijnland Office was the phase of conceptual design: with only one exception all energy saving building components were selected and made to fit into the design during this phase. Only the daylighting system (blinds) was selected during the phase of final design.

The consultant for HVAC-systems joined the design team very early: he was part of the design team when the use of energy saving building components was discussed for the first time. However, this consultant did not use computational tools in the phase of conceptual design. Instead, decisions were based on his earlier projects, and on reference projects. The consultant said to base part of his advice on experience gained from previous computational efforts.

Computational tools (EP calculation method, VA114, PIA-15 and spreadsheet) were used during preliminary design, final design and preparation of building specifications and construction drawings. Calculation of an energy performance coefficient (EPC)[18] is mandatory in the Dutch building code. VA114 is a full dynamic simulation program allowing the simulation of the energy consumption of whole buildings, whereas PIA-15 dynamically simulates one energy saving component (aquifer) only. The tools were used for the following purposes: for confirmation of expectancies concerning energy use, for selection of HVAC-components, and for fine-tuning, optimization and dimensioning of the selected HVAC-components. The tools were not used to compare the performance the selected energy saving building components with other available components or combinations of components in order to support an informed design decision. The only exception was once more the daylighting system: here different design options (window arrangements, types of blinds, translucent insulation material, reflective ceiling) were compared using lighting simulation software and an experimental set-up, resulting in the selection of blinds.

As far as can be observed from the interviews the tools were suitable to obtain the information they were expected to generate.

3.3.3. ECN Building 42, Petten

A - Background of the selection of energy saving building components

The brief for ECN Building 42 defines the required energy efficiency in terms of the Dutch building code, requesting an EP-coefficient[19] of 0.9 or lower. At that time, the standard requirement for office buildings was an EP-coefficient of 1.6. In doing so, the brief prescribes use of the EP calculation method, while limiting the assessment of the performance for energy efficiency of the building to elements and (energy saving) components that are included in the EP calculation method.

The brief (developed by the principal and the consultant for renewable energy) stimulate the architect to select energy saving building components. Yet as the architect specializes in the design of energy-efficient buildings it is probable that he would in any case have selected a number of those components on his own initiative.

The driving force for selection of energy saving components for ECN Building 42 is to meet the specified EP-coefficient of 0.9 or lower.

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[18] The Energy Performance Coefficient (EPC) is obtained by calculating the energy consumption for the building according to a standardized computational procedure, and dividing this by a reference energy consumption. An EPC-value of 1.0 therefore means that the energy consumption equals the reference consumption. Over the years, as energy efficiency requirements increased, this has been reflected by the reduction of the mandatory value of the EPC-coefficient (Nederlands Normalisatie-instituut, 2001a; Nederlands Normalisatie-instituut, 2001b; Ministerie van VROM, 2001).

[19] See footnote 18 for an explanation of the Dutch EPC.

B - Procedure for the selection of energy saving building components

The energy saving components for ECN Building 42 are all selected by the architect during the phase of conceptual design, based on consideration of heating, cooling, ventilation, daylighting and use of renewable energy. For each of these aspects he adds components: for heating an (existing) cogeneration unit; for cooling fixed shading devices and a nocturnal ventilation system; for ventilation a combination of a natural and a mechanical ventilation system, including heat exchangers; for daylighting a number of atria; and for renewable energy photovoltaic arrays. In order to convince the principal to accept these energy saving building components the architect, consultant and principal visit a number of projects in which these components are integrated.

The actual selection of the energy saving building components is not guided by performance requirements. Only after completion of the conceptual design both architect and consultant calculate the EP-coefficient to verify whether or not the design meets the value of 0.9.

As for the impact of the energy saving building components on other performance aspects only the thermal comfort (risk of overheating) of the atria is assessed, albeit in the later phase of final design.

C - Role of computational tools in the selection of energy saving building components

For the selection of energy saving building components for ECN Building 42 the phase of conceptual design was crucial: all energy saving building components were selected and integrated during this phase. No tools were used during conceptual design; instead, all design decisions were based on the earlier projects of the architect and the consultant.

Computational tools (EPC-calculation tool, VABI-tools, TRNSYS) were used during preliminary design, final design and the preparation of building specifications and construction drawings to check whether expectations concerning the building behavior would be met by means of calculation of the EP-coefficient, energy use, and by assessing thermal comfort by means of degree hours. The EPC-tool and VABI tool have been described above; TNRSYS is a fully dynamic thermal simulation program.

These computational tools were also used to optimize the dimensions of energy saving building components and the HVAC-components, and appear to have been suitable for that role. However it is clear that computational tools did not influence the selection of energy saving building components in any way.

3.3.4. Dynamic Office, Haarlem

A - Background of the selection of energy saving building components

The brief of the Dynamic Office requires an office building in accordance with (at the time) current market standards; it does not state any specific requirements regarding energy efficiency. However, it does include requirements for thermal comfort: the tenant wants the building to have a maximum of 150 weighted degree hours as defined and computed by the VABI simulation tool VA114.

All energy saving building components integrated in the Dynamic Office except the atria (façade with overhangs, thermal mass, energy-efficient lighting, energy-efficient computers) are introduced by the consultant for HVAC-systems. The main goal of the introduction of these components is to meet the thermal comfort requirements. An increased energy efficiency is an extra ambition of the consultant, but certainly not the principal objective. The atria are introduced by the architect, in order to deal with daylight access to a low and deep building.

B - Procedure for the selection of energy saving building components
The procedure for selection of energy saving building components is based on repeated computational assessment of the thermal comfort during the phases of preliminary and final design. Each time the requirements are not yet met, new components are added to get closer to the required value. From that point of view, the energy saving components in the Dynamic Office should rather be named 'thermal comfort enhancement components'. The one exception are the atria, which are introduced by the architect during conceptual design in order to allow daylight into the building.
In this procedure, it is clear that the requirement for thermal comfort is an essential factor; however, during the process there is no computational assessment of the impact of the specific components on other performance aspects, like energy efficiency. This comes at a later phase only, when the selection of these components has been finalized.

C - Role of computational tools in the selection of energy saving building components
The design process of the Dynamic Office did not aim at an energy-efficient building from the start; during the phase of conceptual design the architect developed a regular building concept. During the later phases the consultant was the driving force to turn this concept into an energy-efficient design, and introduced a number of energy saving building components.
An interesting fact is the introduction of both specific requirements concerning thermal comfort and the prescription of use of the computational tool VA114 (a full dynamic simulation program) by the tenant. Surprisingly the requirements apparently could be relaxed after discussion of computational results.
During the design process of the Dynamic Office the use of computational tools did influence the building design process and its product; particularly changes in the design of the façade can be seen as a reaction on computational outcomes. Most other energy saving building components (thermal mass, energy-efficient lighting and energy-efficient computers) have been introduced as a reaction on computational results, too. VA144 was suitable to assess thermal comfort in the building. Yet the VA114-tool was not used to compare building performance for a number of possible energy saving building components, resulting in choice of the best component. Instead, all available options to reduce overheating to a minimum were applied.

3.3.5. Cross-case Analysis
The process models of the three cases have been compared with each other in order to see if there is enough common ground for a general view on the selection of energy saving building components and the use of computational tools in these prestigious building projects.

A detailed study of all elements of the IDEF-0 process models shows that only approximately 10% of all activities and less than 20% of the concepts (inputs, outputs, controls and mechanisms that connect these activities and impact their execution) are common to all three models. It is noted that this is partly due to the standardized phasing of the design process which results in the recurrence of the activities of feasibility study, conceptual design, preliminary design, final design and preparation of building specification and construction drawings and accompanying concepts. Furthermore the approval of intermediate designs is repeated. Within the three cases, the moments for selection of energy saving components and use of tools have been analyzed, see figure 3.7 (showing the moment of selection of the energy saving building components for the three cases) and figure 3.8 (showing the moments of use of tools in the three projects).

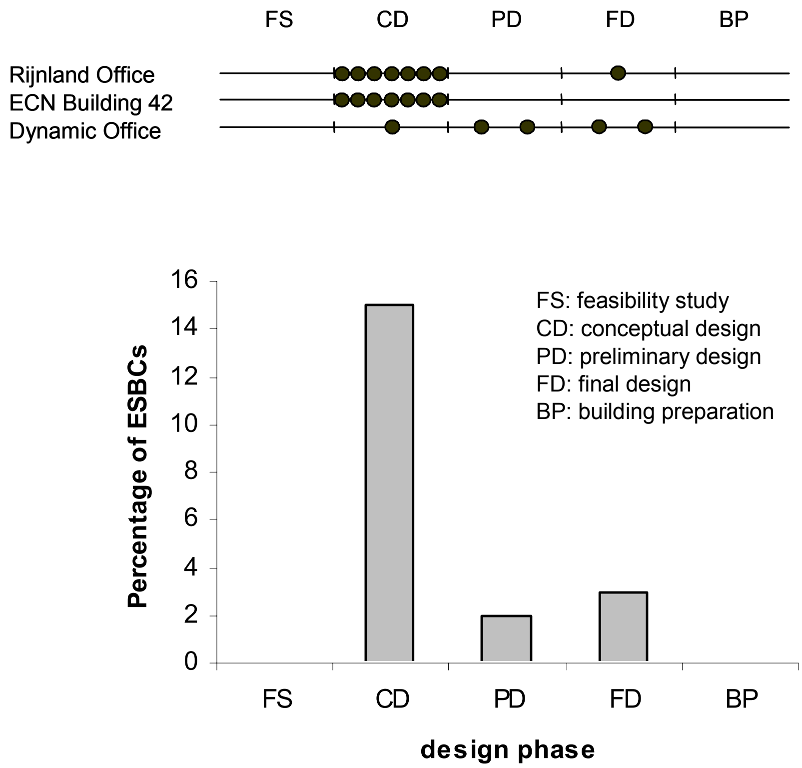

Figure 3.7: Selection-moments of energy saving building components in the three cases, individually and aggregated

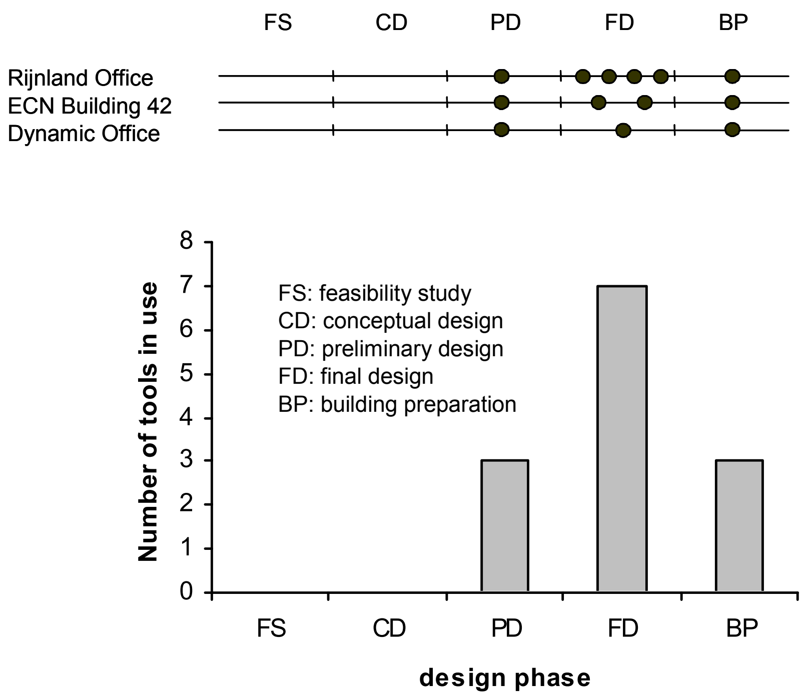

Figure 3.8: Use of tools in the three cases, individually and aggregated

The common elements (activities and concepts) of the three process models and the findings on selection-moments of energy saving building components and use of tools have been used to develop one diagram that captures the common findings regarding the selection of energy saving building components and the use of computational tools. See figure 3.9. Note that the rest of the activities (90% of the total) and concepts (80%) are project-specific and do not return in the common view.

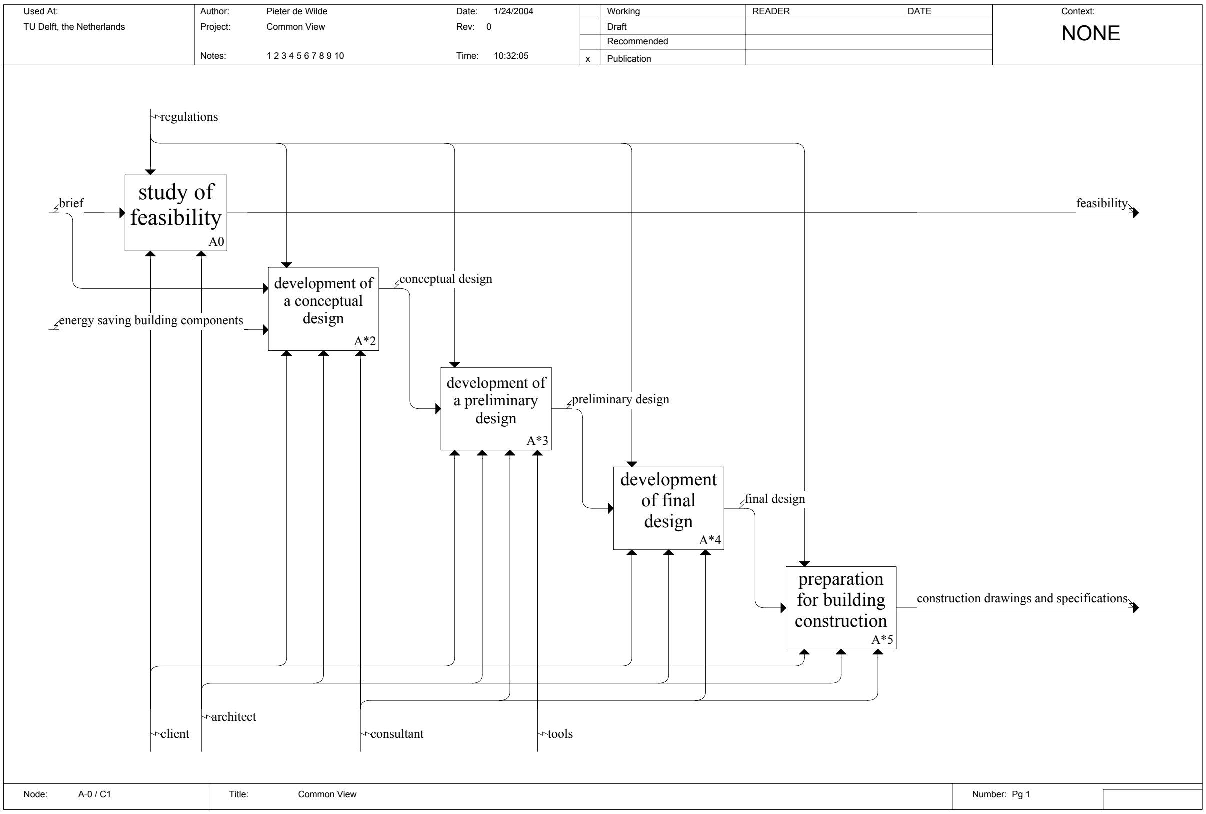

Figure 3.9: IDEF-0 process diagram describing the common view on selection of energy saving building components and use of computational tools as found in the three cases

The common process view reflects the following observations:

- Selection of most energy saving building components takes place during conceptual design.
- Selection of energy saving building components is based on the use of these components by architects or consultants in earlier projects, or is based on the use of these components in reference projects.
- There is virtually no selection of energy saving building components based on an equivalent comparison of the performance of several design variants.
- Computational tools (in the three cases mainly the EP-method and a range of full dynamic simulation tools) are used after the phase of conceptual design has been finished.
- Computational tools are used to verify expectations about building energy use or to optimize the performance of selected components; these tools are not used to support selection of energy saving building components from a range of options.

As far as could be assessed from the case-studies computational tools provided the (performance) information that was the objective of their use; in this sense the tools were suitable for use in the design processes. However, this does not allow any conclusions about the adequacy of the information requests made by the design team.

3.4. Survey

The three case studies provide in-depth information on a limited number of subjects. The results are qualitative and based on open observation, which allows a good insight into the subject-matter. However, the limited number of only three cases resulted in a need to study the representative ness of the three cases for the design process of buildings with energy saving building components in general. As case studies are labor-intensive this aspect has been studied using another, more appropriate research method: by conducting a survey.

Main goal of the survey was to verify whether or not the results of the before-mentioned case studies and cross-case analysis hold for a larger sample. Specifically the following research questions about buildings with energy saving building components in general were to be answered:

- In which phase(s) of the design process have energy saving building components been selected? Are most energy saving building components selected during the phase of conceptual design, as indicated by the case-studies?
- Based on what arguments does selection of energy saving building components take place? Are most energy saving building components selected based on experience and use in demonstration projects, as indicated by the case-studies?
- Have computational tools been used? If computational tools were used, in what phase of the design process did this usage take place? Do the results confirm that computational tools are mostly used after selection of energy saving building components has taken place?
- What were the reasons to use computational tools? Are the main reasons to use tools verification of expectations about overall building energy use and optimization of the performance of selected components, but not to support selection of individual energy saving building components?

3.4.1. Approach

The first step in conducting the survey was the selection of a set of appropriate building projects. The following selection criteria were used: each building project had to make use of energy saving building components, and the architect and consultant of the project had to be both known and contactable. The search for projects was limited to the Netherlands. Based on these criteria a set of 70 building projects was selected from literature on energy-efficient architecture, including the before-discussed cases. The 70 projects represent the maximum number of recent projects for which the names and addresses of both architect and consultant could be traced and for which a list of applied energy saving building components could be compiled. Note that this is a rather limited sample size, limiting the projection of the findings to all building projects and rendering statistical efforts descriptive rather than inferential.

Questionnaires were developed for the architect and consultant involved in the design of each building project, adhering to basic rules for development of questionnaires (for recent publications on the issue see e.g. Burgess, 2001; Frary, 2002) and enlisting expert help (Tacken, 2000).

- In accordance with the goal of the survey (verification of whether or not the results of the before-mentioned case-studies hold for a larger sample) the questions in the questionnaire address:
  - the phase of the design process in which selection of energy saving building components takes place;
  - the argumentation underlying the selection of specific energy saving building components, including motivation for selection, the range of alternatives that has been considered, and the tools that have been used to support this selection;
  - the use of (computational) tools in the design project, the phase of the design process in which use of computational tools takes place, and the reasons to use these tools.

  For each building project a project-specific questionnaire was developed by linking these questions to the list of energy saving building components as applied in these projects. The majority of the questions were multiple-choice questions about either individual energy saving building components or individual computational tools. This allowed for simple statistical analysis of the results. Open questions were used to gather background information and to gain further insights.
- The questionnaires for architects differed from those for consultants; both were tuned to the specific role of the interviewees. For some of the projects the architect did not employ a consultant; in those cases the architect received a combined / extended questionnaire.
- The questionnaires were tested on architects and consultants of the three cases.

An example of a questionnaires for architects is included in appendix D.

Results from the survey were subjected to a statistical analysis using the software package SPSS for Windows, release 7.5.2 (SPSS, 2002). Questionnaires returned by architects and consultants were analyzed separately. The analysis of returned questionnaires consisted of computation of frequency distributions of answers, representation of these answers in tables and diagrams, and determination of tendencies in these answers. Confrontation of answers from architects with answers from consultants only took place for those building projects for which both architect and consultant did return the questionnaire. Finally the results of the survey were compared with the results of the case studies. As most data from both research activities (case-studies and survey) is not numerical but qualitative, this comparison was executed by hand.

The survey targeted 67 building projects. In those projects a total of 303 energy saving building components have been integrated. The number of components per building varies: in some buildings only one energy saving building component has been integrated, others have as many as nine. On average the projects have four energy saving building components. In 26 buildings all energy saving building components have completely different fields of action; in 37 buildings some overlaps are found. In 7 buildings a number of energy saving building components seems to be redundant, i.e. they appear to overlap substantially with other components.

3.4.2. Results

Response

The number of questionnaires that were sent and received are summarized in table 3.1. The returned questionnaires combine to partial data sets (response from either architect or consultant) for 42 projects and full data sets for 10 projects on a total of 67 projects. Again, note that the overall sample sizes are very limited, and confidence intervals quite broad: for the responses of the 34 architects we find a confidence interval of 12%, for the responses of the 18 consultants the confidence interval is 20%, and for the 10 full sets the confidence interval is 29% (Lohr, 1999; Creative Research Systems, 2002).

	Architects	Architects without consultant	Consultants
Questionnaires sent:	54	13	54
Questionnaires returned:	29	5	18

Table 3.1: Response for the questionnaire

Partial Data Sets

The responses of the 34 architects (including those that did not employ a consultant) can be summarized as follows:

- According to these architects, most of the 204 energy saving building components that were integrated in the related building projects had been selected during the phase of conceptual design (57%). Percentages of energy saving building components selected in other phases are: feasibility study: 16%; preliminary design: 13%; final design: 10%; preparation of building specifications and construction drawings: 4%. See figure 3.10.
- Together the 34 architects were able to name 23 specific alternatives that had been considered for the 204 energy saving building components that they selected. This means that 181 components were selected right away, without consideration of at least one alternative option.
- Most architects (23 out of the 34) did not use any tool at all to support the selection of energy saving building components. If architects used tools, they used checklists, handbooks, other means (like scale models) or combinations of these three. No computational tools were used. Only 7 out of the 34 architects optimized the interaction between energy saving building component and the building themselves using these checklists, handbooks and other means. See figure 3.11.

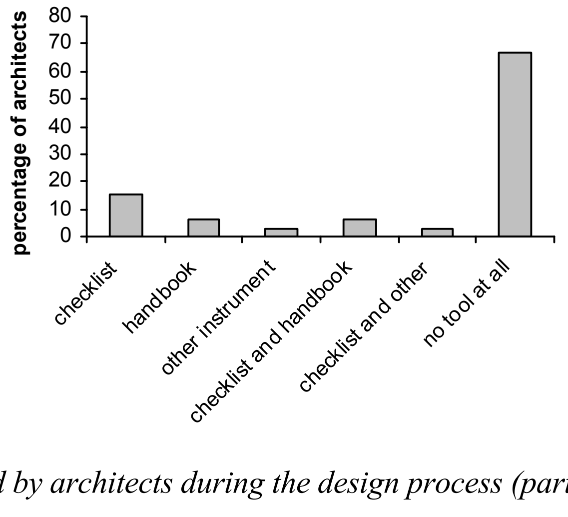

Figure 3.11: Tools used by architects during the design process (partial data sets); N = 34

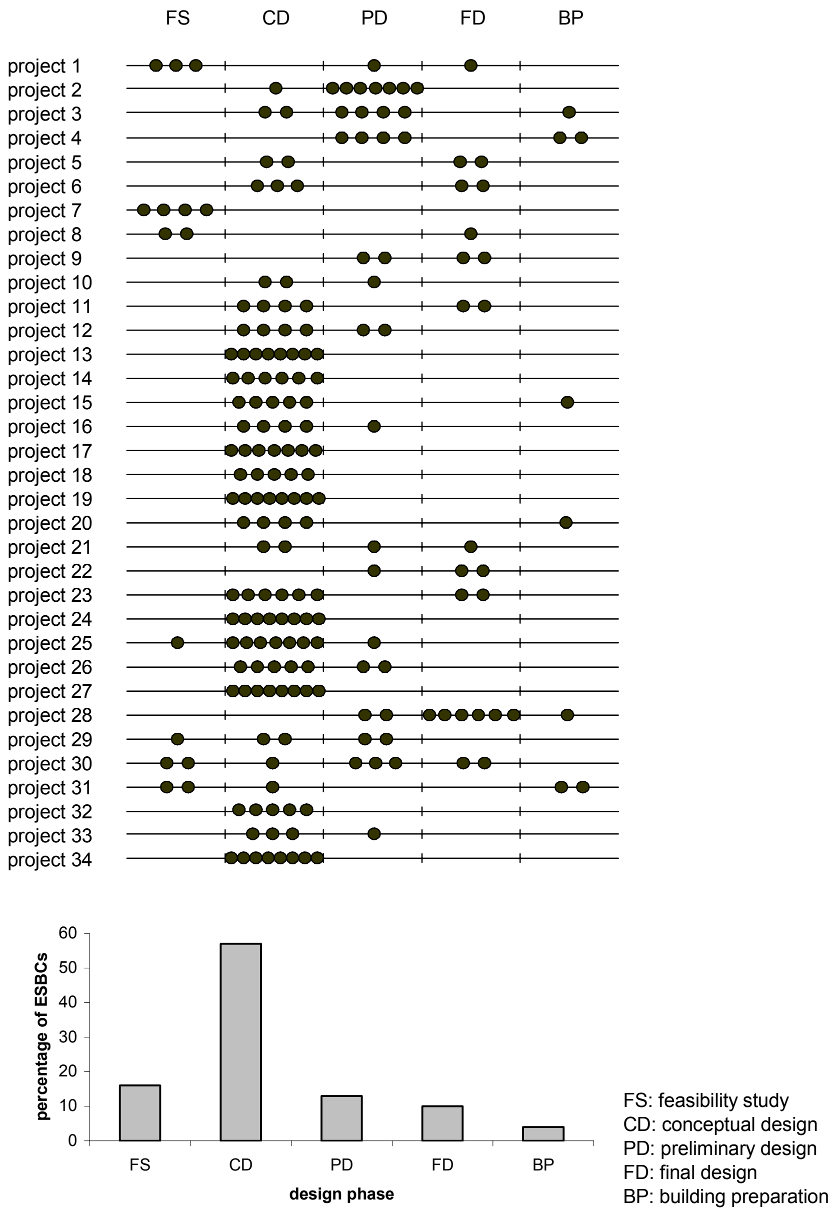

Figure 3.10: Percentage of energy saving building components selected per design phase, according to architects (partial data sets); N = 204

The responses of the consultants can be summarized as follows:

- According to consultants most of 111 energy saving building components in the related building projects were selected during the phase of feasibility study (44%). Percentages of energy saving building components selected in other phases are: conceptual design: 28%; preliminary design: 21%; final design: 4%; preparation of building specifications and construction drawings: 3%. See figure 3.12.

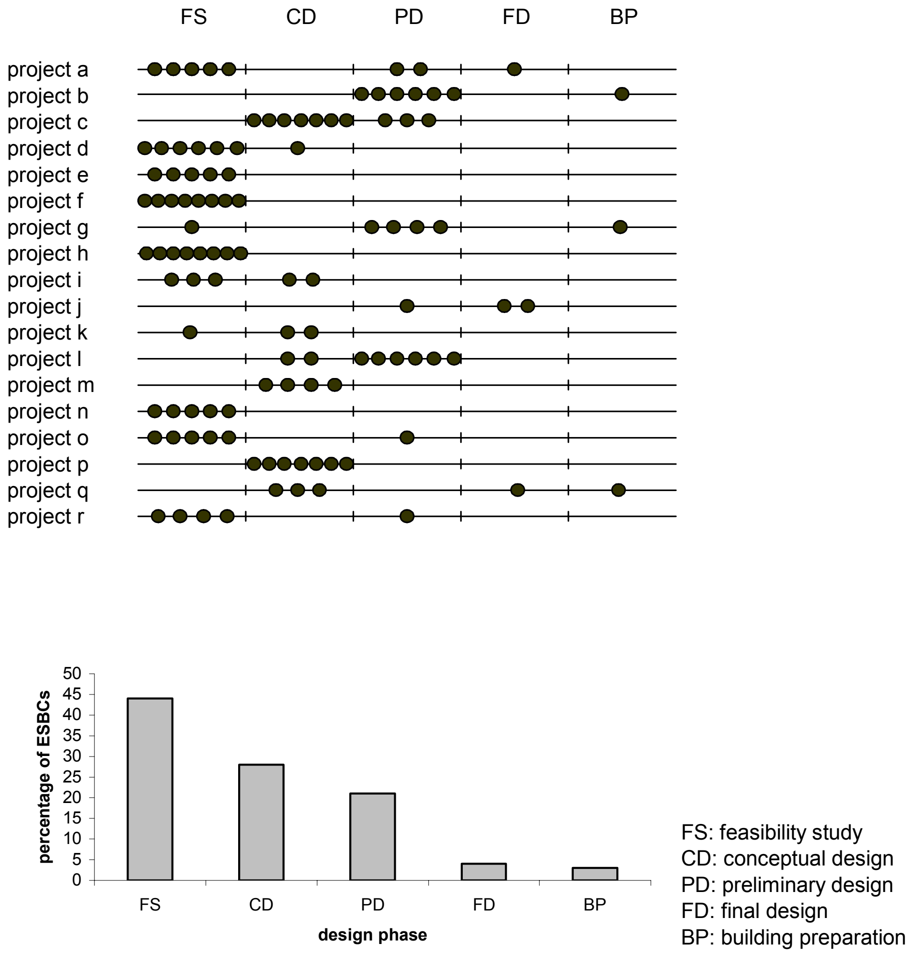

Figure 3.12: Percentage of energy saving building components selected per design phase, according to consultants (partial data sets); N = 111

- Asked to motivate the selection of each one of these 111 energy saving building components consultants mostly named experience and/or demonstration projects (37 %). Other motivations were maximum energy savings (29%), cost-benefit tradeoff (11%) and others (23%). Others motivations for instance are thermal comfort, experimentation with the energy saving building component, component prescribed by the principal etc. See figure 3.13.

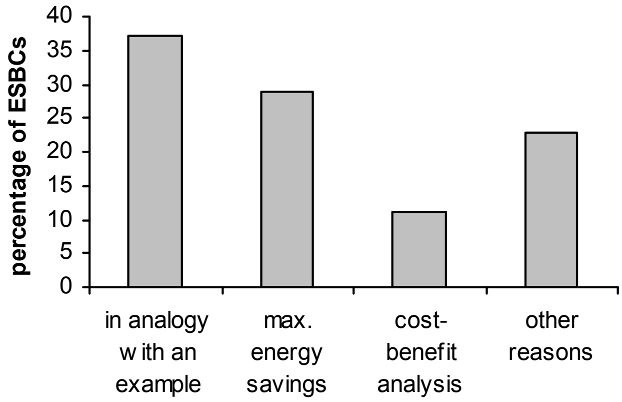

Figure 3.13: Motivation for the selection of energy saving building components, according to consultants (partial data sets); N = 111

- Together the consultants could name 21 specific alternatives for the 111 energy saving building components that were selected in the design projects in which they participated; this means that for only 19% of all energy saving building components they made a choice between competing alternative components.
- According to the consultants, for a total number of 111 energy saving building components:
  - 33 components were selected without any computational assessment at all;
  - 32 components were selected after computational assessment of their efficiency;
  - 57 components were checked for their impact on energy efficiency after they had been selected;
  - 50 components were optimized using computational tools.
- The 18 consultants that returned the questionnaire used a total of 42 computational tools. These tools were used for several purposes: assessment of the energy consumption of the whole building (24%); evaluation of design options (not only related to energy saving building components but also concerning selection of HVAC-components) (30%); optimization of parameters (33%); and other usages like study of thermal bridges, daylighting (13%). See figure 3.14.

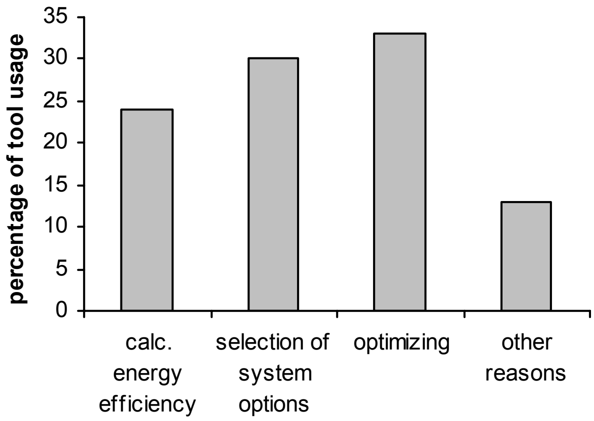

Figure 3.14: Goals of the use of tools during the design process, according to consultants (partial data sets); N = 42

Full Data Sets

For 10 building projects both architect and consultant returned the questionnaire. For these projects answers from both groups have been compared.

- The full data sets show the same findings regarding the moment of selection of energy saving building components as the partial sets: according to the architects in the full data sets most of the 59 energy saving building components in the related projects were selected during conceptual design (55%), whereas according to the consultants in the full data sets most of these components were selected during feasibility study (42%). See figure 3.15.

  Inspection of the individual projects reveals that in 6 out of 10 projects there was a phase gap concerning the selection moment of energy saving components which was consistent across the project, indicating that the consultant perceived decisions to be taken one or two phases ahead of what the architect perceived. In one project the architect was ahead of the consultant, and in 3 projects there was no phase gap.
- The full data sets gave no additional insights regarding the motivation for selection of energy saving building components.
- Regarding the phase in which computational tools were being used the results showed that many computational efforts started early in the design process, but took quite some time to be completed. Often there was a time-lag of one or two phases before the results found their way to the architect. Even if tools were used during the feasibility study, architects reported receiving results only after the phase of conceptual design. See figure 3.16.
- The full data sets gave no additional insights regarding the motivation for the use of computational tools.

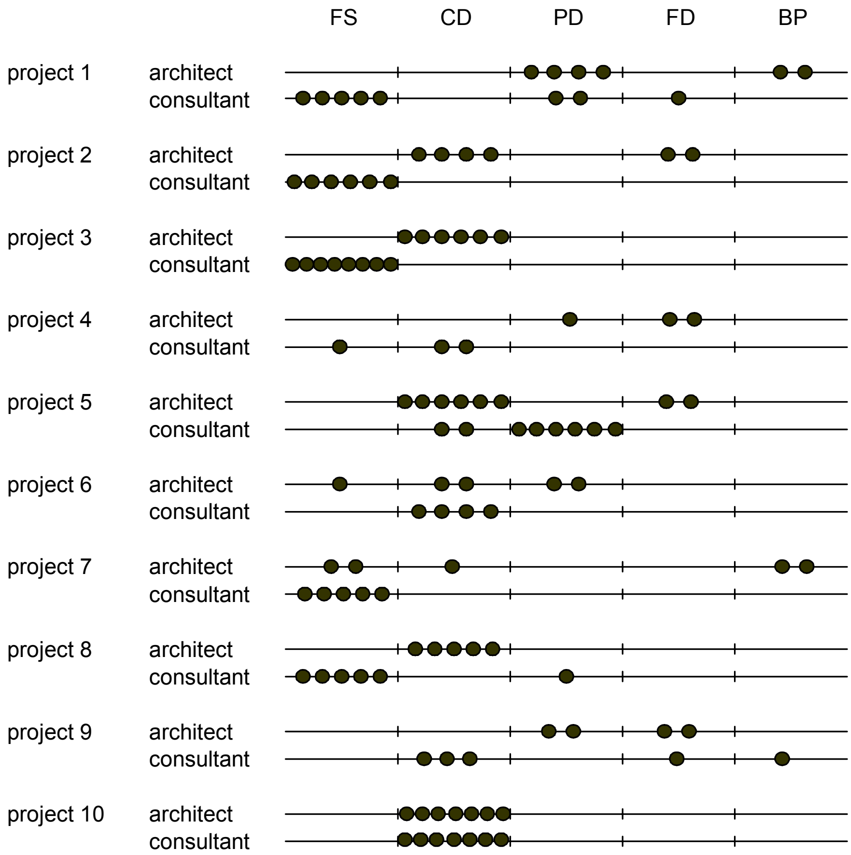

Figure 3.15: Energy saving building components selected per design phase (full data sets)

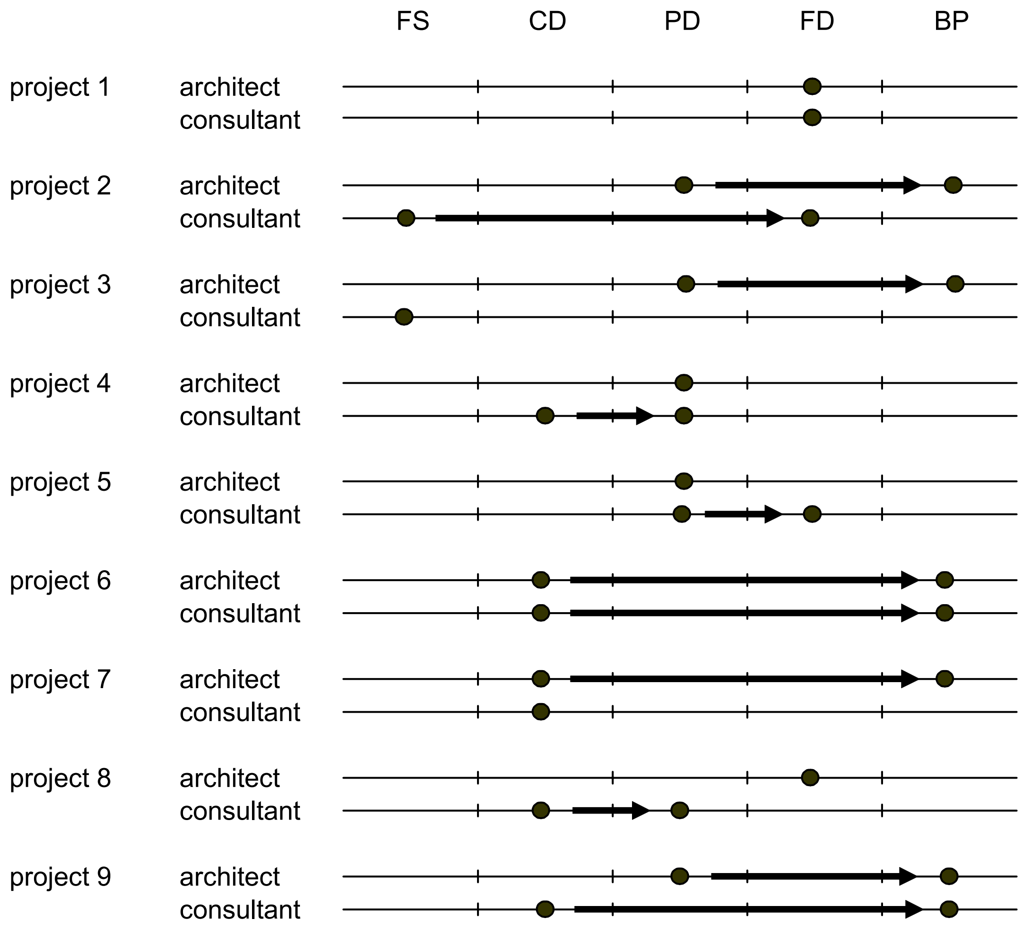

Figure 3.16: Use of computational tool per design phase, showing start and end of tool use as indicated by consultant, and showing the period in which architects report to have received computational results (full data sets)

3.4.3. Findings of the Survey

The data that has been collected through the survey itself allows the following conclusions:

1. The trends in the partial data sets, the full data sets as well as the results for individual building design projects all show that architects and consultants had different perceptions concerning the phases in which energy saving building components had been selected. Therefore it was not possible to determine one common distribution of the selection moments of energy saving building components over the phases of the building design process. However, the general finding was that 70% to 72% of all applied energy saving building components (according to architects and according to consultants) had been selected at the end of the conceptual design phase.
2. The most important motivation for the selection of energy saving building components was earlier use of similar components in previous buildings, or knowledge of use of energy saving building components in demonstration projects. Architects based approximately 41% of their choices of energy saving components on this argument, consultants 37%. Other important reasons were maximization of energy savings, and selection based on a cost-benefit tradeoffs. Many more motives were found; some of these are thermal comfort, architectural expression, use of energy saving building components to gain experience, or selection based on available subsidy.

In this context it is important to note that two thirds (23 out of 34) of the architects did not use any tool at all to support their choice. Consultants said to support the choice of only one third (29%) of all energy saving building components with computational tools.[20]
3. The results obtained from consultants clearly showed that computational tools were used during the phases of conceptual design, preliminary design and final design, though use in other phases was observed as well. The results also show that it took some time for computational results to materialize. This was confirmed by the view of the architects, who experienced that most computational results were obtained during the phase of preliminary design or later, and consequently after selection of energy saving building components had taken place.
4. The main reasons to use computational tools were optimization of parameters, verification of earlier design decisions, and support of all kind of design decisions still to be made (including some decisions concerning energy saving building components). Differences between the three were small; each accounts for approximately one third of al computations. It must be strained, however, that in spite of these results about 70 percent of all energy saving building components was selected without computational support.

The overall conclusion from the results of the survey (bearing in mind the possible impact of the limited sample size) is that most energy saving building components are selected without computational underpinning. Instead, the selection of these components seems to be mainly based on earlier use and analogy. Approximately 80% of all energy saving building components are selected without considering alternatives, which demonstrates that the decision to select a specific component is highly intuitive. Thereby the findings of the survey are in line with the findings of the case-studies, and confirm the representative ness of the results of the case studies for a larger sample.

A striking additional insight resulting from the survey is that architects and consultants appear to have different perceptions concerning the phases in which energy saving building components had been selected. This conflicts with the expectation that the activities of all participants in the design process are interrelated and all contribute to achieving the common goal: the design of an building that meets all requirements. The reasons for these different perceptions remain unclear; possible explanations could be a lack of interaction (the proverbial exchange of evaluation request and computational results by writing) or a possible under- or overestimation of specific activities or contributions. Also, consultants might experience their own involvement as the start of the design process, even if this coincides with a later phase of the overall design process. However, this does not explain all differences, as the same results have been obtained for projects where the consultant joined the design team in the very beginning.

3.5. Discussion and Conclusion

The main goal of this chapter is to analyze the current way of selecting energy saving building components during the design of energy-efficient building projects, and to analyze the role of building energy simulation tools in the selection process. In order to achieve this goal this chapter analyses real, prestigious contemporary building projects in the Netherlands by means of case-studies and a case-study related survey.

[20] There is no relation between this two third and one third figure; these values are coincidental.

The research steps described in this chapter result in the following conclusions:

- Selection of energy saving building components mostly takes place early in the design process: during the phases of feasibility study and conceptual design. Use of computational tools has been found to start during these early phases, yet results from computational efforts do not reach the architect before the phase of preliminary design. It therefore is concluded that the selection of most energy saving building components is not impacted by the use of computational tools.
- There is little evidence of design teams making multiple-criteria design decisions to choose components from a set of different alternatives. Most decisions only consider energy efficiency. Only a small subset of energy saving components in the projects was selected from an set of alternatives that consisted of at least one other option.
- The case-studies and survey show that computational results are not available at the moments selection of energy saving components takes place. Therefore it is unlikely that performance requirements play a role in the decision making process. Only later in the design process (preliminary design, final design and preparation of building specifications and construction drawings) is the overall energy efficiency of buildings with integrated energy saving components verified. Hence, selection of these components seems based on (unquantified) efforts of the design team to make the building energy-efficient.
- As will be clear from the preceding finding the contribution of computational tools on the selection of energy saving components is very limited. After selection has taken place, computational tools are used for optimization and verification purposes. Because of this finding it is not possible to give a meaningful discussion of the type of computational tools that is used in current practice to support the selection of energy saving building components , or to discuss the suitability of these tools.
- The main motivation for the selection of energy saving building components is earlier use of these components in previous projects by the architect or consultant, or the integration of these components in reference projects.
- Many previous and ongoing efforts aiming at integration of computational tools and the building design process try to address the issue through technological developments, like the automation of building energy performance analysis, automated data transfer between analysis tools and architectural (CAD) tools, and by hiding complexity from users through (graphical) user interfaces (see chapter 2). However, the findings of this chapter clearly show the need to address both the building design process and computational tools at the same time. As long as selection of energy saving building components takes place in an intuitive manner[21], based on previous use by the decision makers and analogy with demonstration projects, computational results will have little impact on the selection procedure. The other way round, unavailability of meaningful computational results at the moment that a decision about selection of energy saving building components is relevant means that the decision has to be made in an intuitive manner. Therefore, chapter four of this thesis will deal with the process of selecting energy saving components, and chapter five will deal with tools that provide support for this process.

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[21] Note that the use of intuition does not necessarily results in buildings with a lesser performance. However, the use of rational, multiple-criteria decision rules using computational results does make the decisions more transparent, negotiable and justifiable. Providing hard proof that this actually results in better buildings will be difficult if at all possible. However, existing buildings that fail to meet performance criteria (user complaints, sick building syndrome, larger-than-expected energy bills) and that contain energy saving building components that have overlapping functions indicate that intuition does not always lead to good decisions.

Remarks:

- Literature on decision-making in design (Roozenburg and Eekels, 1991) points out that simplified decision rules are often used when design teams are confronted with complex situations; these simplified rules deliberately neglect part of the information. These rules include searching for design options that meets the requirements, and stopping as soon as a satisfactory option has been found (conjunctive rule/satisficing); a search for an optimal solution for one arbitrary aspect only (disjunctive rule); or a search that considers further aspects only as long as different options remain (elimination by aspects). Overall, the main characteristic of these methods is that they converge quickly on one solution, without an assessment of all advantages and disadvantages of many different alternatives. It is highly probable that, due to the lack of feasible alternative decision methods (and applicability of those methods in practice), similar rules are used for the selection of energy saving building components.
- Fay (2002) observes that in the building industry, 'of concern in the use of case-studies, particularly where quantitative data are not provided, is the uncertainty about the validity of the claims made about the building. Experiments are not always successful and case studies of innovative buildings or buildings claimed to represent best practice cannot be regarded as authoritative unless backed by credible data and benchmarked against widely accepted standards, whether for energy, water consumption or any other attribute'. As long as this concern remains, the use of analogy and reference projects as a basis for the selection of energy saving components seems doubtful.
- Regarding the methodology of the research described in this chapter the following observations are made:
    - The level of detail of the case studies in this research is limited by the fact that these case have been analyzed afterwards. At least one other layer of detail could be added to IDEF-0 process models by studying design processes in real-time observation. However, this will require a long observation period; a typical design process as described in this chapter takes approximately one year. Moreover, the outcome and even the completion of a design process cannot be predicted in advance, making it hard to select a case for this kind of study. Even more important is to question whether an extra layer of detail will reveal relevant information. The results of case studies performed after the design has been finished already reaches a level of detail where most design activities become project-specific; probably the extra detail added by real-time study of cases will be project-specific, too.
    - IDEF-0 process modeling has some limits. IDEF-0 models are focused on the activities that require input and produce output; IDEF-0 is less suited to capture informal communication patterns, iterations between different process levels etc. (Malmström *et al*., 1999). Although an effort has been made to include such links in the process models of the cases, it is hard to say whether this has been successful. Also, IDEF-0 models are not suitable for the support of future building design processes, as they are a rigid, multi-layered description of specific processes; they cannot be easily adapted to the characteristics of some new, specific building design process.

- For future research the following issues are deemed relevant:
  - Real-life observation of ongoing building design processes might add extra information on the selection of energy saving building components and the use of computational tools in practice to the basics that have been provided by the work presented here. However, overcoming the mentioned practical problems to obtain sufficient relevant information will be difficult.
  - The scope of the case studies and survey in this chapter are mainly technical. Only little attention has been paid to the roles played by the different actors, their social interaction, and the way these factors influence the decision-making process. This provides another area of research which can be expected to have a large impact on the selection of energy saving building components. Actual rationalizing of decision-making in daily practice will have to include this aspect.
  - The work presented in this chapter only assesses the building design process itself. A valuable addition to this work could be made through profound analysis of the combination of design process in relation to its product, the final building design, or even the resulting buildings. Ideally such a study should combine process analysis, computational study as well as monitoring, resulting in insights in the relationships between design process, 'quality as designed' and 'quality as build'.
  - In this chapter, only single design processes are studied. An investigation that maps the design process of a number of consecutive design processes by one and the same design team might reveal interesting interconnections between these individual projects, providing better insights into the use of experience across projects.

4. Underpinning the Selection of Energy Saving Building Components

"The true system, the real system, is our present construction of systematic thought itself, rationality itself, and if a factory is torn down but the rationality which produced it is left standing, then that rationality will simply produce another factory. .... There's so much talk about the system. And so little understanding."

(Robert M. Pirsig)

The previous chapter demonstrates that in current building design projects the selection of energy saving building components mainly takes place in an intuitive manner, based on earlier use of the same components in previous buildings and in analogy with demonstration projects. Also, it concludes that computational tools are not used to support the selection of energy saving building components.

This chapter deals with the selection procedure for energy saving building components. The main goal is to develop an approach for well-founded selection of these components. In doing so, it addresses the research question of how the current way of selecting energy saving building components can be improved (see 2.5). The approach that is developed in this chapter is to be applicable during the early design phases, and must enable maximal use of computational tools. Possibilities for improving tools to better support the selection process will not be addressed in this chapter, but will be discussed in chapter five.

In order to reach the goal, two research questions need to be answered:

- which opportunities exist to arrive at a well-founded choice of energy saving building components?
- how can an approach for the well-founded selection of energy saving building components be developed?

In order to answer the research questions the following research steps have been taken: analysis of existing opportunities to make a well-founded choice, and development of an approach for a well founded selection of energy saving building components (de Wilde *et al.* 2001b, de Wilde *et al.* 2002a, de Wilde *et al.* 2002b).
The analysis of existing opportunities to make a well-founded choice of energy saving building components, which is described in paragraph 4.1., consists of:

- analysis of the requirements and constraints that can be identified for making a well-founded choice, and that must be met by any approach that tries to improve the selection procedure for energy saving building components (paragraph 4.1.1);
- overview and assessment of existing theories for making design decisions and specifically for selection of building components, resulting in identification of gaps and missing aspects in existing theories (paragraph 4.1.2).

The development of an approach for a well-founded selection of energy saving building components is described in paragraph 4.2, and consists of:

- development of an approach for performance-based design decision-making on the selection of energy saving building components, using applicable elements from existing theories to define the essential steps that should be taken and where needed structuring the sequence and interrelations of these steps (paragraph 4.2.1);

- analysis of the viability of the resulting approach by means of application of the approach to an example, allowing evaluation of whether or not the resulting approach meets the requirements and constraints as identified in the first step, and fills the gaps in existing theories (paragraph 4.2.2).

Paragraph 4.3 concludes the chapter by summarizing the results of this chapter, and by presenting conclusions and remarks.

4.1. Analysis of Opportunities

From the findings of the research presented in chapter three it is concluded that the current way of selecting energy saving building components is based on simplified, heuristic decision rules. This paragraph analyzes the opportunities to improve the procedure for the selection of energy saving building components by analyzing the requirements that must be met when making a well-founded design decision regarding the selection of such components, and by analyzing existing theories that might be used to support a well-founded choice.

4.1.1. Requirements for a Well-founded Selection

The following criteria apply if the selection of energy saving building components is to be considered a well-founded design decision:

1. the selection must be based on a choice between a set of alternatives (buildings with energy saving building components), ensuring that different options have been considered;
2. when deciding between the different alternatives, all relevant performance aspects must be taken into account;
3. for each design alternative information about the performance for each of the relevant performance aspects must be available, allowing a comparison of advantages and disadvantages.

These criteria ensure that the search for energy saving building components includes more than only one alternative, allowing the decision to select the best option from a range of alternatives. They also ensure that not only energy efficiency is assessed, but other relevant building performance aspects (especially thermal comfort) as well. Finally, they call for design decisions to be made on the basis of performance information, which allows to rationalize these decisions.

It must be noted that an approach for the selection of energy saving components must be applicable in the context of an ongoing building design process. This means that the procedure must:

- be applicable during the early phases of the building design process (feasibility study, conceptual design), since it is in these phases that most energy saving building components do get selected;
- only target the selection of energy saving building components. It is important to note that selection of these components is only one of many activities that takes place during the building design process. Other, unrelated activities must not (or only minimally) be constrained or impacted by the approach.

4.1.2. Existing Theories

An existing body of knowledge (which has been discussed in paragraph 2.1.2) is available in the field of engineering design that addresses rational design decision-making. This body of knowledge relates to design decisions about (sub)systems. In order to investigate the applicability of this knowledge to the selection of energy saving building components, a system view of these components is explored; the extend to which this theory meets the criteria for a well-founded choice will be analyzed.

In a systems view of energy saving building components, selection is to be seen as the making of decisions on the use of specific building (sub)systems. From this perspective, selecting and combining elements into a (building) design is basically a search for sub-systems that allow the overall building to perform all required functions. The functions of the building can be specified using aspect-systems like daylighting system, energy system, etc.

Following the definition of sub-systems given in chapter two[22], it is clear that energy saving building components qualify as sub-systems (parts and sections) of a building. The energy saving building components listed in appendix A are tangible, distinct material constructs that can be integrated into a building. As buildings consist of a hierarchy of sub-systems, it is logical that many energy saving building components are part of larger sub-systems. For instance thermal insulation, solar windows or skylights are all part of the building enclosure sub-system; heat pumps, cogeneration units and solar collectors are part of the HVAC sub-system; and PV-cells and energy saving lighting elements are part of the electrical sub-system. The other way round, energy saving building components can also consist of a number of sub-systems themselves, like a cogeneration unit which is made by combining a heating-apparatus and power-generator. In some cases one energy saving building component can even contain other energy saving building components, like a sunspace containing PV-cells and advanced glazing systems. This sub-system view of energy saving building components is important in distinguishing different alternative design options. It plays a role when ensuring that different options have been considered (requirement 1 for making well-founded decisions on the selection of energy saving building components).

Studying the functional relationships between energy saving building components and the building provides insight into the aspect-systems (in terms of functional relationships) of which these components are elements. By their nature all energy saving building components are part of the overall energy aspect-system, which consists of all building parts that in some way influence the energy use of the building. However, since energy saving building components can be based on different principles, they might be part of different aspect-systems lower in the hierarchy of aspect-systems: for instance light shelves and (reflecting) blinds are part of the daylighting aspect system, wind turbines and photovoltaic arrays are part of the power generation aspect-system, and aquifers, energy piles and thermal mass are part of the energy storage aspect system. Note that it is very well possible for one energy saving component to be part of a number of aspect systems: for instance a sunspace can be part of the daylighting, thermal insulation, ventilation and sheltering aspect-systems. The aspect-system view of energy saving building components is important to identify the functions that any given energy saving building components performs. It plays a role when ensuring that all relevant performance aspects are taken into account (requirement 2 for making well-founded decisions on the selection of energy saving building components).
When a (building) design meets the requirements, the sub-system view (describing the parts of the system) must meet the aspect-system view (describing the functions of the system).

[22] See section 2.1.2.: sub-systems are parts and sections of a building that might exist at any stage of the building design and construction process

Finding the match between possible configurations and required functions is the heart of the selection procedure. See figure 4.1.

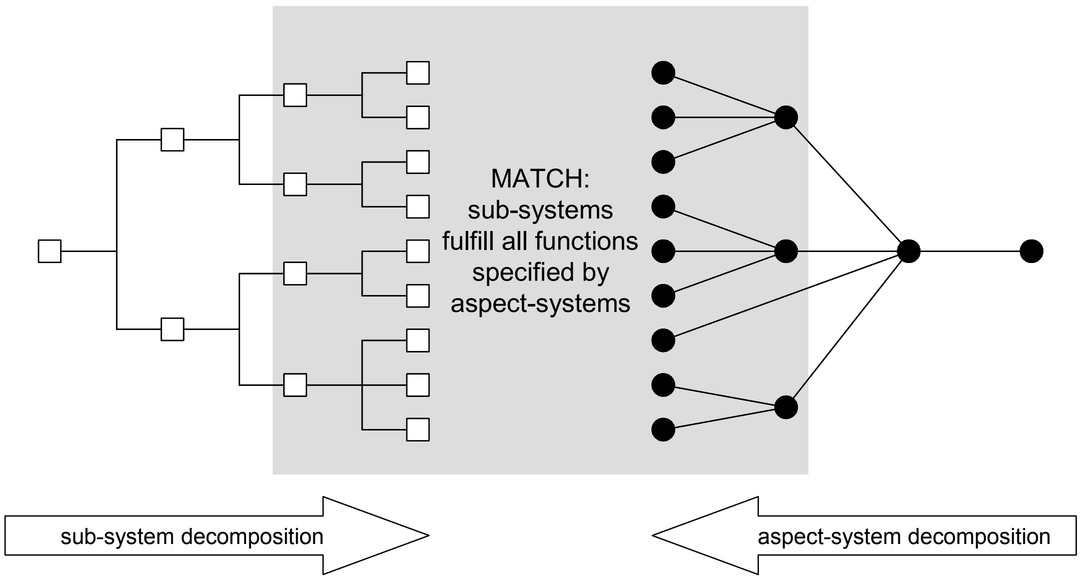


Figure 4.1: Match of sub-system view and aspect-system view

As discussed in paragraph 2.1.2. qualification and quantification of the (sub)system performance for each relevant aspect is the key to making a well-informed choice between different alternatives (requirement 3 for making well-founded decisions on the selection of energy saving building components). Once this performance information is available, decision theory can help to make subjective values explicit and to make a rational choice.

From the above it is clear that the body of knowledge on rational design decision-making addresses all requirements for a well-founded selection of energy saving building components. However, it fails to provide a clear roadmap for the steps that must be taken to select components according to this theory. This has its origin in the fact that this is general theory, which is applicable to different engineering domains and addresses all major life-cycle stages of the systems concerned. In order to obtain the approach for selection of energy saving building components elements from this body of knowledge need to be identified and combined into a specific selection procedure.

Besides the theory on rational design decision-making a number of well-known other theories, techniques and methods is available that have been developed to improve the quality, reduce costs, increase productivity or responsiveness of engineering, design and manufacturing processes. These other theories all re-structure (design) processes in certain ways. A short overview of the most important theories, in alphabetical order, is given below:

- Concurrent Engineering (CE) is a systematic approach for integrated, concurrent design of products and related processes including manufacture and support. This approach is intended to cause the developer to consider all elements of the product lifecycle from concept through disposal, including quality control, cost, scheduling and user requirements (Society for Concurrent Product Development, 2002).

- Integrated Product Development (IPD) is a philosophy that systematically employs a combination of functional disciplines to integrate and concurrently apply all necessary processes to produce an effective and efficient product that satisfies the customer's needs (Society for Concurrent Product Development, 2002).
- Quality Function Deployment (QFD) is a quality management and control system that is designed to ensure interaction between the design, development, engineering, manufacturing and service process, and the need of a customer. Part of Quality Function Deployment is the use of an assembly of matrices named the 'house of quality' which represents and relates customer requirements, technical requirements, and planning (QFD Institute, 2002).
- Robust Design / Taguchi Methods are techniques for quality engineering that include both statistical process control and quality related management techniques, allowing to improve productivity in generation of new knowledge (iSixSigma, 2002).
- Value Engineering (VE) is a systematic and organized procedural decision-making process, that has been used in many different kinds of application. It supports the generation of alternatives that secure essential functions at the greatest worth, as opposed to costs. This is referred to as value. Value Engineering uses a job/task plan, is function based, and requires a product be generated as a result of the study. Alternative names for Value Engineering are Value Analysis, Value Management, Value Planning (VeToday, 2002).
- Finally there is a set of methods that are tailored for specific design objectives, like Design for Manufacture and Assembly (DFM/A), Design for Maintainability and Serviceability, Design for Reliability, Design for the Environment (DFE), or Design for Testability (DFT). These methods all adhere to more or less similar approaches and differ mostly in their focus on specific performance aspects.

All of the mentioned theories aim at rational and manageable processes. The approaches vary from strongly product-focused (e.g. concurrent engineering or value engineering) to more procedure-focused (e.g. integrated product development). They all address the requirements 1, 2 and 3 for well-founded design choices, albeit with different focusing points. They all have in common that they are general theories for design and production processes as well. Yet in order to provide a procedure for the selection of energy saving building components and in order to define the individual steps that must be taken with respect to the selection of these components a more specific approach is needed. Also, note that many of these theories have their background in the theory of rational design decision-making. An approach built from elements from rational design decision-making will fit within many of the above-mentioned more general theories, like concurrent engineering or value engineering.

From this overview and analysis of existing theories it is concluded that there is a body of knowledge that addresses the making of well-founded design choices. Much of this knowledge is part of the theory on rational design decision-making as described in paragraph 2.1.2.; other theories and approaches like concurrent engineering, integrated product development, quality function deployment, robust design, value engineering etc build on this knowledge while emphasizing different aspects (process, product). However, all of this knowledge is rather general. It is applicable to different engineering domains and across different life-cycle stages of the engineering systems concerned. Since the knowledge is of general applicability it provides useful elements for a well-founded selection of energy saving building components, but does not include a clear roadmap or step-by-step plan for the selection of these components.

4.2. Development of an Approach for the Selection of Energy Saving Components

In this paragraph, elements from existing theories are used to develop an approach for performance-based selection of energy saving building components. Assumptions and constraints that govern the development of the approach are introduced, followed by presentation of the individual steps of the approach. The approach is then applied to an example, demonstrating how it would work in a real design project and allowing evaluation of the approach using the criteria as defined in paragraph 4.1.1.

The approach for selection of energy saving building components will be based on the premise that a design process contains a series of decision moments. At each of these decision moments a choice is made between a number of alternative design options. Furthermore, it is assumed that these design decision moments can be isolated from the rest of the design process, which makes it possible to rationalize decision-making at these moments and to provide support for making these decisions.

While the approach intends to help in evaluating options and selecting one alternative, the approach is not intended to have any impact on the way these alternatives are created. The development of the alternatives is open to the creativity of the design team. There is no limitation of the creative process, and the design team with its expertise remains an essential element in performance-based design.

4.2.1. Basic Steps

Based on the knowledge from engineering design, the following steps appear as the essential elements of a design decision-making process on selection of energy saving building components. For each step, possible options to support this specific step are discussed.

1. *Development of an option space:*
   The first step in making performance-based design decisions is to identify which alternative design options are to be considered; in systems engineering the set containing all options is named the option space. Options can be generated by definition of different system configurations (combinations of sub-systems, for instance combinations of a building design with different energy saving building components) and by changing the parameters of these system configurations. For specific design situations it is possible to identify specific parameters which can be varied over a permissible range; this is named parametrization of the option space. It is recommended to include the initial building design, without extra energy saving component, as zero-option.
   Regarding the definition of system configurations it is noted that the research presented in chapter three revealed that in most projects the option space for selection of energy saving building components is virtually empty: it was found that 80-90% of all components were selected without consideration of alternatives. Formal development of an option space will stimulate the design team to broaden their search. On the other hand, it is imperative that the option space contains a manageable, finite set of options. Evaluation of all possible combinations of a building design with all available energy saving building components (complete enumeration and subsequent selection of the optimal solution) is not within reach: it is easy to develop a host of different system configurations, which are all subject to variable parameters, and thereby to explode the option space to unmanageable dimensions. For this reason expert knowledge and expertise regarding the design under

development remain essential to success, since only experts in the field will be able to develop an option space that contains the relevant and most promising design options. Looking at the building that is used to start the development of the option space, it is clear that the building design can take many shapes, from a design that is defined by a volume and a building function only up to a completely defined existing building for which all details are known (as encountered in renovation projects). However, as the most important phase for the selection of energy saving building components is conceptual design (see chapter three), conceptual building designs will be central in the development of the option space.

One way to support development of an option space for energy saving building components and to prevent the consideration of many inappropriate components might be the development of a morphological chart (Cross, 1994; Roozenburg and Eekels, 1991), which helps to arrive quickly at a number of components that could be useful for a specific design. A morphological chart list essential functions of a design under development, adds the means by which these functions might be achieved, and allows to combine these different means to achieve all functions and thereby to define possible options for a design project. An example of a small part of such a morphological chart is presented in figure 4.2.

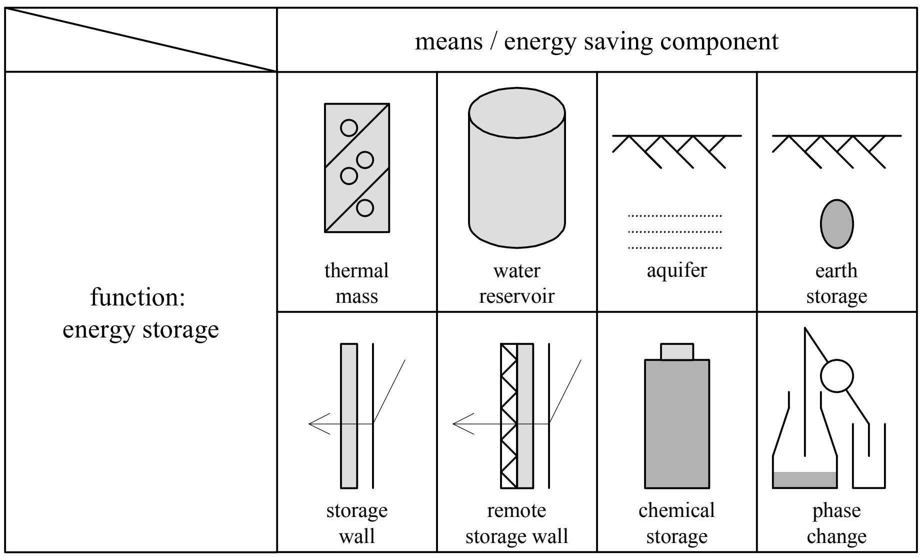


Figure 4.2: Example of a part of a morphological chart for the selection of energy saving building components

Another way to provide support for the development of an option space is to study each energy saving building component and compile a set of relevant parameters. The range of these parameters is either defined by the building design or by external factors. For instance the maximum area of the separating wall between a sunspace and the adjacent building is limited by the building design, whereas the COP (coefficient of performance) of a heat pump depends on physics. Parameters that relate to the building design are named design dependent parameters; the other parameters are named design independent parameters. A catalogue of energy saving components that gives the design team easy access to design-dependent parameters, design-independent parameters and their respective limiting factors will help to speed up the definition of the option space. Efforts trying to identify which parameters are most important for specific performance aspects of specific building types are already going on in the research community (e.g. Purdy and Beausoleil-Morrison, 2001).

2. *Identification of the relevant functions of the design options:*
In parallel to the development of the option space, thought must be given to the functions that these design options must fulfill. Identification of the relevant functions (performance aspects) is essential for finding the relevant criteria for making the pending design decision. Obviously, the main function of the use of energy saving building components is to make buildings more energy-efficient. Yet energy efficiency is only one of many objectives that must be considered in the building design process; the notion of 'energy-efficient building design' as a mono-discipline is clearly fictitious. For instance an important function relevant to many energy saving components is the building function of maintaining thermal comfort. A rational selection of energy saving building components is only possible if different functions are identified and considered. Those functions are related to the aspect-systems to which the components belong.
It is imperative that the set of relevant intended functions (criteria) remains manageable, too. Again, expertise is essential. In cases where the expert evaluating the options is not the building designer, negotiation and discussion should lead to a finite set of functions/criteria that will be evaluated.

A way to support design teams in identifying relevant functions of energy saving components would be to develop an overview of relevant aspect-systems and functions per energy saving building component. See figure 4.3. for an example.

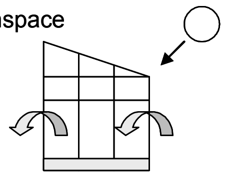
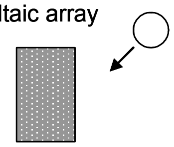
Energy saving building component	**Relevant aspect systems**	**Potential functions**
sunspace 	• space enclosing system • heating system • daylighting system • ventilation system • ….	• provide additional useful space • allow solar access to building • pre-heat ventilation air • decrease transmission losses • ….
photovoltaic array 	• electrical system • space enclosing system • ….	• electrical power production • electrical power self-sufficiency • provide climate barrier • ….

Figure 4.3: Example of an overview of relevant aspect-systems and functions per energy saving building component

On a higher level, an overview of possible building functions and related performance aspects (a performance ontology) might be helpful. This performance ontology could be presented in the form of an objective tree which shows design objectives (functions) in a diagrammatic form, clarifying relationships of objectives (functions) and showing the hierarchy of objectives and sub-objectives (functions and sub-functions). See figure 4.4.

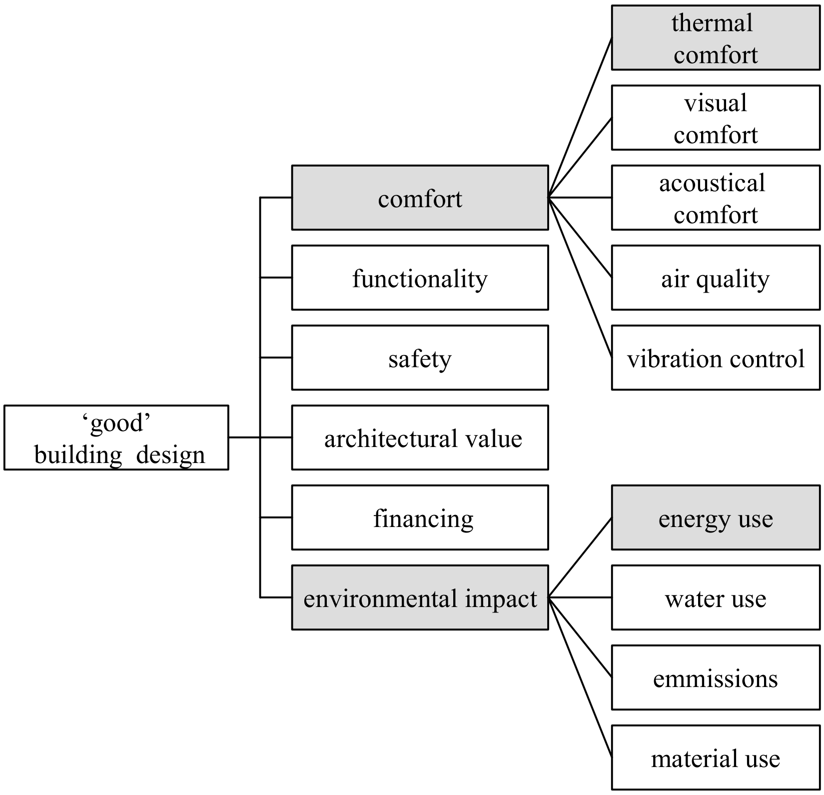


Figure 4.4: Performance ontology in the form of an objective tree

3. *Specification of performance indicators, objectives, requirements and constraints:*
   Once the relevant functions of the alternative design options have been identified, (technical) performance indicators must be selected that describe how well these options perform their functions; performance indicator values will represent the performance of all alternative options. It is important that the list of performance indicators is complete (adequately covers all relevant functions), operational (meaningful), and non-redundant (preventing double counting of the same achievement). Additionally, the set of performance indicators should help to decompose the relevant functions into manageable, measurable performance aspects, while at the same time being of minimal size.
   Note that performance depends on the interaction of a system with its environment. Therefore the explicit definition of the (virtual) experiment that will be carried out needs to be included in the definition of the performance indicator. For instance, the main function to 'make the building energy-efficient' can be measured using the energy-consumption per year, or using peak heat demand. However, an energy consumption value for a given design option is meaningless when it does not come with a specification of the types of energy use that are studied (heating, cooling, lighting), the location for which the energy consumption is predicted (for instance Atlanta or Amsterdam), the occupant behavior and HVAC control that is assumed (operated all year, only in weekends). As performance indicator for thermal comfort one could use PMV or PPD values, but again,

those only make sense with a specification of the occupant, the activities and clothing of this occupant, climate data etc.
Performance indicator values have a range. In this range values can be identified that the design team wants to achieve; those values are named objectives or goals. Other values must be met in order for the design to be acceptable; those values are named requirements. Functions that come with requirements are named constraints. Note that in most design projects the principal only provides general needs and wishes. Actual objectives, constraints and requirements are frequently linked to actual design options and hence need to be defined during the course of the design process.

Additional support for the specification of performance indicators, objectives, requirements and constraints that are relevant for the selection of energy saving building components could be provided by a database that contains an overview of different performance indicators that are usable to quantify given performance aspects. This database could even be linked to the performance ontology suggested in the previous step, allowing a quick link between identification of relevant functions and the way these functions will be quantified. Limiting values (representing common objectives and/or requirements) might also be included.

4. *Prediction of performance*:
As the performance of a design option (building plus energy saving component) is a function over the properties of these options when subjected to specific conditions, an experiment is needed to measure or predict this performance. Since the building does not yet exists, the most easy option is to conduct a virtual experiment using building performance analysis tools running on computers. The resulting set of performance indicator values is named outcome space.
Theoretically the outcomes should be expressed in terms of predicted performance and associated probability of occurrence, because of uncertainty in the design itself, the conditions in which the design will function, and the prediction method. However, studies of propagation and implications of uncertainty in virtual experiments are relatively rare in design contexts; risk and uncertainty assessment of building performance prediction have been receiving attention only recently (de Wit, 2001; Macdonald, 2003). For the time being deterministic values are often accepted.[23]
As will be clear from chapters two and three, existing tools are only rarely used in current building design projects to predict performance in such a design decision context. Yet within the procedure to select energy saving components the use of analysis tools is straightforward, consisting of selection of a tool that is able to return performance indicator values for the design options as specified in the previous steps, and of carrying out the experiment as required. Missing links to allow easy choice of an applicable tool are an overview of which performance indicators can be produced by the various performance analysis tools, and an overview of which building design options can be represented in these tools. Further investigation of this issue, linking decision-making process and the use of tools will be presented in chapter six.

23 As long as uncertainty cannot be quantified, it is mandatory to use the same performance analysis tool to predict the same performance indicator value for the comparison of different design options in order to minimize errors introduced by different calculation procedures, modeling assumptions etc.

5. *Evaluation of predicted performance and selection of the most desirable option*:
First, all options must be checked for meeting the requirements; options that not meet those are ruled out. The remaining options must be ordered based on the extent to which they meet the objectives. This implies that (subjective) values must be assigned to the data in the output space, resulting in the utility of each option for each performance aspect (function). In order to make a tradeoff between the different utilities for the different performance aspects (functions), an additive utility function can be used. This tradeoff is subjective once more. However, by using an additive utility function the underlying value structure is made explicit and negotiable. In that case it is important that all utilities are measured according to the same scale, allowing to compare the different performance aspects. An example of a common scale can be:
   0.0 = does not meet the objective
   0.5 = just meets the objective;
   1.0 = perfectly meets the objective.

   The definition of additive utility function is given by:

$$U(A_i) = \sum_{j=1}^{m} \lambda_i e_{ij}$$

Formula 4.1: additive utility function

where:

$U(A_i)$ =	utility of alternative A_i with regard to all criteria $C_1, \ldots, C_m$
A_i =	alternative i, i = 1, …, n
λ_j =	weighting factor of criterion C_j, representing the 'importance' of C_j to the overall utility
e_{ij} =	effectiveness of alternative A_i related to criterion C_j
C_j =	criterion j, j = 1, …, m

(Roozenburg and Eekels, 1991).

   Support for the selection of energy saving building components can be provided by a spreadsheet-application in which all performance predictions are brought together in a performance matrix. The application can then allow the design team to assign (subjective) values to all performance data in the matrix, thus transforming it into an assessment matrix. Finally the application can allow the design decision maker to enter weighting factors and return overall utility values that can be used for making the final decision.

The five steps that have been described above can be executed in this order; however, in real design practice some iteration and concurrency must be accommodated. For example, development of the option space and identification of relevant functions can take place in parallel, or evaluation of the performance of a set of options might lead to the decision to add an additional building design alternative to the option space. This is represented by the general roadmap of the approach as depicted in figure 4.5.

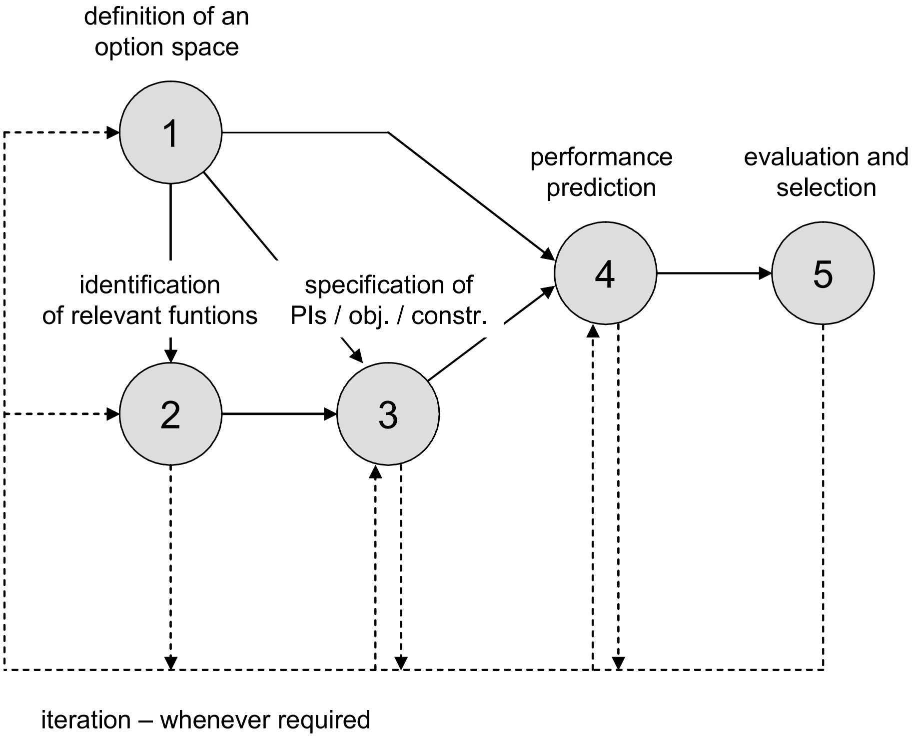


Figure 4.5: General roadmap for the selection of energy saving building components

4.2.2. Example

This section demonstrates the application of the procedure to a case, which has been set up to be in line with the case-studies described in chapter three. All steps of the procedure will be discussed in detail.

Case description:

The case focuses on a design decision that needs to be made during the phase of conceptual design of a small office building in the Netherlands. See figure 4.6. The following outline has been established: the building consists of an arrangement of office cells with standard dimensions (5.4m x 3.6m x 2.7m). The office building will have two floors. Both floors consist of six cells on one side, a wide corridor (5.4 m) that houses stairs and a large opening to connect the upper and lower level of the corridor, and four more office cells across the corridor, two on each end of the building. The remaining space in the middle of each floor holds the entrance and a reception desk (first floor), coffee corner and copy machine (second floor), stairs and restrooms. The entrance faces due south; the building is situated on a site which has free solar access on all sides. The load-bearing structure will consist of concrete slabs and columns. Inner walls will be of a layered construction of gypsum/glasswool/gypsum. The office cells will have doors to the corridors, and windows on the other side (window area is 35% of the façade). Both ends of the corridor will be fully glazed. No decisions on an HVAC-system have been made.

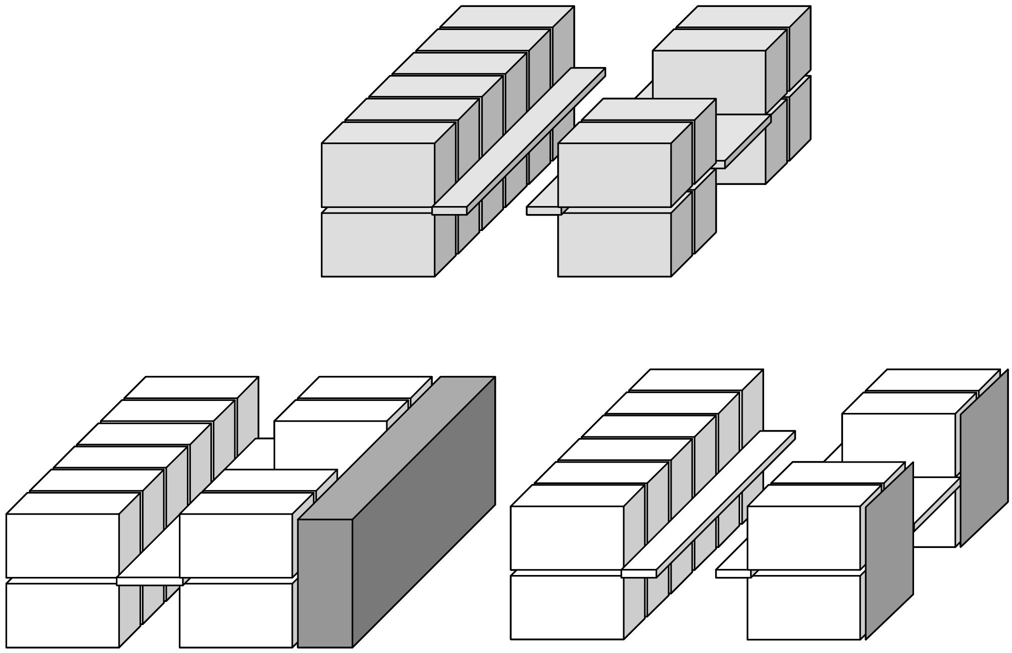


Figure 4.6: Example: conceptual office design, with two design options

To this design concept the design team wants to add an energy saving building component. After discussion two energy saving components are considered a real option for the scheme: addition of a two-story sunspace as extension to the southern façade, or application of photovoltaic arrays integrated in the south facing façade[24]. See figure 4.6.

Exemplary design decision-making process:

- *Option space*:
  The first step in applying the procedure for selection of energy saving building components to the case as described above is definition of an option space. Even though the building design is described in some detail and two qualifying energy saving building components have been pre-selected, there is still need for further definition, as both components still allow for infinite variation. For instance, the sunspace can be completely separated from the offices by internal walls/glazing or partly separated from the offices by means of (glazed) doors, or can be fully integrated with the entrance/coffee corner (open, no partition). Dimensions of the sunspace are not yet defined, nor is materialization (glazing type); and the sunspace might have different sunshading and ventilation options. The photovoltaic arrays can be made of amorphous, polycrystalline or crystalline cells, while different numbers and sizes of modules can be selected; different options regarding grid-connection, batteries for storage, inverters etc. are possible, and there are many ways to integrate PV into a façade.

[24] Note that these components are also used in the case-studies discussed in chapter three: all three cases had either sunspaces or atria, while ECN Building 42 had photovoltaic arrays integrated into the roof of the sunspace.

Typically the definition of the option space will result from discussion between the building designer and the expert consultant. This discussion is a part of the selection process where knowledge and expertise remain essential, no matter what support instruments are being developed. In this case it will be assumed that the building designer and expert consultant have agreed to assess the following five design options:

- Option 1: building design 'as-is', without addition of any energy saving building component (neither sunspace nor PV).
- Option 2: building plus isolated sunspace (dimensions 3.6m x 6.0m x 21.6m); partitioning between offices and sunspace is 100% single glazing, outer shell of the sunspace is double glazing. In order to maintain a similar building volume /size the width of the corridor is reduced to 1.8m. The load bearing structure of the sunspace consists of aluminum profiles. There is no air exchange between sunspace and office; the sunspace does have blinds that go down as the temperature in the sunspace exceeds 25 ^{o}C.
- Option 3: identical to option 2. However, now the sunspace is used during the winter to pre-heat ventilation air for the offices. In summer the sunspace remains fully isolated.
- Option 4: integration of polycrystalline PV in a façade consisting of aluminum frame, fully glazed with integrated Venetian blinds; the PV-cells will double as sunshading device and be integrated in the glazing. Cells are 0.125m x 0.125m; each office cell has 5 rows of cells at balustrade level, 5 rows at ceiling level; in front of each office cell are 28 columns of PC-cells. Electrical power not used in the office will be provided to the net of the local utility company.
- Option 5: identical to option 3, but with amorphous PV instead of polycrystalline.

- *Objectives and constraints, performance indicators:*
In order to define the criteria for selecting one of the design options, the relevant functions of the options must be identified. In real design projects, identification of these functions again will result from discussion between the building designer and the expert consultant, needing expert judgment. For the example, assume that the building designer and expert consultant have agreed that the following functions are essential:
    - Function 1: make the building energy-efficient
    - Function 2: maintain thermal comfort in the offices (constraint)
    - Function 3: minimize additional embodied energy in the production of the building (constraint)
    - Function 4: provide additional useful space (specific function of sunspace)
    - Function 5: make building self-sufficient regarding electrical power (specific function of PV)

Quantification of how well the four design options fulfill these five functions requires specification of applicable performance indicators. Performance indicators need to come with the definition of the virtual experiment by which the performance indicator values will be measured. The following performance indicators can be used:

- PI_1: energy-efficiency:
Energy-efficiency can be quantified by computing the sum of the heating and cooling load per year for any given option, and dividing this by the sum of the heating and cooling load per year for a reference case. Since the idea is to decide between different energy saving building components it makes sense to make the reference case equivalent to design option 1.

A precisely defined virtual experiment must be developed from which these cooling and heating load can be observed. The description needs to include experimental set up, testing conditions applied, and observed states:

- Experimental set up: consists of the elements of the building design options 1 to 5 that will be taken into account in the experiment. The offices on one level on the north side can be considered to form one zone; on the south side, each cluster of two offices will be one zone. Corridors, reception, stairs and coffee corner will also be represented by one zone. Assumptions need to be made about the façade: for all non-glazed parts a construction of 0.100 m concrete, 0.100m mineral wool, 0.050m cavity and 0.050m concrete (inside to outside) will be assumed. As the HVAC system is not yet defined, an idealized HVAC system will be assumed.
- Testing conditions: the experimental set up will be tested for climate data for the Netherlands according to the test reference year (deBilt.TRY). The test is carried out for free field conditions. For occupant behavior, working hours from Monday to Friday and from 8:00 AM to 6:00 PM are used; public holidays are discarded. Furthermore, it is assumed that each office is used by two employees, each providing 100W. Each employee uses a computer during all working hours, also providing 100W. Artificial lighting is on the whole day, and provides an additional heat source of $15W/m^2$. The reception and coffee corner are taken to contain 2 persons of 100W, and 1 PC of 100W. For the idealized heating system, it is assumed that during office hours a minimum temperature of 20.0 ^oC is maintained, as well as a maximum temperature of 22.5 ^oC. During non-office hours, the temperature is maintained at a minimum of 10.0 ^oC, whereas there is no maximum limit in place.
- Observed states: for the above experimental set up the heating and cooling load per year are observed. Note that there only is an idealized HVAC-system in place.

o PI_2: thermal comfort:
Different performance indicators can be used to quantify thermal comfort, the most notable being the PMV and PPD as developed by Fanger (1970). However, the most easily observed state of rooms or zones is an average air temperature; from this one can measure the number of hours that a given temperature is exceeded. In the example such a measuring of hours that the temperature of the zones exceed a given limit will be used, assuming a threshold value of 25.0 ^oC.

- Experimental set up: equivalent to PI_1.
- Testing conditions: equivalent to PI_1.
- Observed states: temperature of each zone (hourly measurement). From the values obtained for the different office zones, one average number of exceeding 25.0 ^oC will be calculated, relative to floor area.

o PI_3: additional embodied energy in producing the building:
This performance indicator quantifies the energy used to acquire raw materials and manufacture, transport and install the energy saving building components during the initial construction of the building. It does not include the energy associated with maintaining, repairing and replacing materials/components. This quantification can take place by measuring the types and amounts of materials used in the energy saving component and multiplying those with standard embodied energy values.

  - Experimental set up: consists of the design of the sunspace and PV-arrays as described in options 2, 3 and 4. Option 1 has no additional embodied energy.
  - Testing conditions: consist of virtual production, transport and installation of the energy saving building components in the building, using average or default values for transportation distances, loss/breaking rates during installation etc.
  - Observed states: amount of energy used in production to installation of energy saving building components.

- PI_4: additional useful space:
  Addition of useful space is a function which is specific to the energy saving component sunspace. However, the space provided by sunspaces cannot be used during the whole year, since the temperature regime in a sunspace is different and the function of saving energy prevents use of HVAC-equipment in this space. Therefore added area must be multiplied with a factor representing usability of the space from a thermal comfort point of view; this factor can be calculated by dividing the number of hours that the temperature in the sunspace is in a comfort zone by the total number of office hours in a year.
  - Experimental set up: consists of the sunspace as described in options 2 and 3.
  - Testing conditions: the experimental set up will be tested for climate data for the Netherlands according to the test reference year (deBilt.TRY). The test consists of free field conditions. For occupant behavior, working hours from Monday to Friday and from 8:00 AM to 6:00 PM are used; public holidays are discarded. Blinds and ventilation regimes are applied as specified in option 1 and 2.
  - Observed states: average air temperature in the sunspace; the number of office hours that this temperature is equal to or higher than 18.0 ^oC and lower than 28.0 ^oC is to be measured.

- PI_5 : electrical power self-sufficiency:
  Electrical power self-sufficiency can be quantified by computing the percentage of electrical power consumption by a building that is generated by building-integrated PV.
  - Experimental set up: consists of all electrical appliances in the office (computers and lighting) as well as the PV-arrays integrated in the south-facing façade.
  - Testing conditions: assume electrical power use to be completely independent of outer climate, and only dependent on office hours (Monday to Friday, 8:00 AM to 6:00 PM, public holidays are discarded). Irradiation data is according to climate data for the Netherlands described by the test reference year (deBilt.TRY). The effect of PV-temperature, inverter conversion, overload, inhomogenities, pollution of the PV-arrays etc can be neglected.
  - Observed states: power production by the PV arrays, and power use by the electrical equipment in the building. It is assumed that power production that exceeds demands is provided to the net, and that this compensates for power supplied by the net to the building at a different time.

- *Prediction of performance:*
  The virtual experiments described above are carried out to obtain performance indicator values for all options. For most of the performance indicators thermal simulation is

needed to obtain these values: PI_1 requires thermal simulation to obtain heating/cooling loads per year; PI_2 and PI_4 require thermal simulation to obtain hourly average air temperatures for specific building zones; and PI_5 requires thermal simulation to obtain the hourly power production by the PV-arrays.

In the example use has been made of the multi-zone transient heat transfer simulation program Capsol (Physibel, 2002), since this tool provides the information needed for PI_1, PI_2, PI_4 and PI_5. This state-of-the-art tool is selected based on availability/accessibility. Other simulation tools that could have been used include for instance ESP-r, TRNSYS, or EnergyPlus (DOE-2 / Blast). In addition to Capsol use has been made of Microsoft Excel. Further discussion about the use of this tool is not presented here, as this concerns the usability of existing tools to support the procedure which is assessed in chapter five. Further specifics of the use of Capsol to provide the performance indicator values is presented in paragraph 5.2.1. PI_3 has not been calculated; fictive values have been used instead.

Resulting Performance Indicator values:
Table 4.1 represents the performance indicator values that have been obtained by using Capsol, Excel and doing some calculations by hand:

	PI_1	PI_2	PI_3	PI_4	PI_5
Option 1	1	23.8	0	X	X
Option 2	0.89	0	9	44.3	X
Option 3	0.91	0	9	44.3	X
Option 4	1.03	15.7	5	X	2.9
Option 5	1.04	15.7	4	X	1.4

Table 4.1: Performance matrix

Remarks on the results:

- Option 4 and 5 actually decrease the energy efficiency, since the façade in which the PV elements are integrated is a fully glazed façade which comes with increased transmission losses.
- Option 2 and 3 have the effect of increasing the thermal comfort in the office space, since the blinds in the sunspace also help prevent overheating in the offices, whereas the options without sunspace are simulated without blinds.

Alternatively, these results can also be presented in graphical format. See figure 4.7.

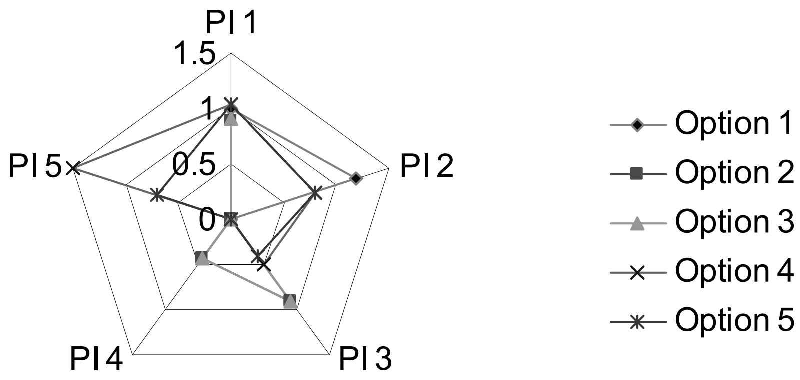


Figure 4.7: Performance indicator values represented in a radar plot

- *Evaluation and selection:*
  As no objectives/constraints are available to rule out an option, all options must be ranked based on the extent to which they meet the objectives. This implies assigning a (subjective) value to the performance data. In this case the above data is assessed using the following scale:
  0.0 = does not meet the objective;
  0.5 = just meets the objective;
  1.0 = perfectly meets the objective.
  The table with performance indicator values can now be converted to an following assessment overview or assessment matrix. See table 4.2.

	(PI_1)	(PI_2)	(PI_3)	(PI_4)	(PI_5)
	score:	score:	score:	score:	Score:
Option 1	0.5	0.3	1.0	X	X
Option 2	0.9	1.0	0.5	0.7	X
Option 3	0.8	1.0	0.5	0.7	X
Option 4	0.4	0.4	0.6	X	0.6
Option 5	0.4	0.4	0.7	X	0.7

Table 4.2: Assessment matrix

The overall utility of the options can now be calculated by assigning weighting factors to the different objectives (different performance aspects). For instance, the following weighting factors might be used (of course, in a real design context these factors would be assigned after in-dept discussion between architect, consultant and/or principal):
$PI_1 = 40$, $PI_2 = 20$, $PI_3 = 20$, $PI_4 = 10$, and $PI_5 = 10$. Using these factors one can calculate the additive utility value for each design option using formula 4.1, resulting in the following overview. See table 4.3.

	(PI_1)	(PI_2)	(PI_3)	(PI_4)	(PI_5)		U(A)
Weighting Factor:	40	20	20	10	10		
Option 1	20	6	20	X	X		46
Option 2	36	20	10	7	X		73
Option 3	32	20	10	7	X		69
Option 4	16	8	12	X	6		42
Option 5	16	8	14	X	7		45

Table 4.3. Weighting matrix

Based on this performance information and subjective weighting factors, selection of option 2 would be a rational decision.

4.2.3. Evaluation

The following criteria have been defined in paragraph 4.1.1. for a well-founded selection of energy saving building components:

- the selection must take place as a choice from a set of alternatives;
- the selection procedure must take into account all relevant performance aspects;
- the decision must be based on performance information.

Furthermore, it must be noted that selection of energy saving building components takes place in early phases of the design process, and that the selection of these components should not interfere with other, unrelated activities in the design process.

The first criterion is met by the step of developing an option space. The example demonstrates that this is no trivial activity: explicit specification of all design alternatives that will be considered in the selection process is a prerequisite for arriving at a well-founded choice.

The second criterion is met by the fact that the approach ensures a multi-criteria decision that not only assesses energy efficiency, but other relevant building performance aspects (especially thermal comfort) as well. This is achieved through explicit analysis of the functions that the building design options must fulfill, and the specification of matching performance indicators.[25]

The third criterion is met through performance prediction for all options and relevant performance aspects, leading up to a rational choice using decision rules that combine quantification of performance with subjective values. This allows the design team to guarantee that the selected option will indeed meet given performance criteria. However, the step of performance prediction implies that the design team must take care to obtain valid information. In most cases this will require the use of building performance analysis tools.

Regarding operational issues, the approach is demonstrated to be applicable to early design phases (especially feasibility study and conceptual design): the example represents a typical

[25] Note that the approach also allows to define only one function and one performance indicator, thereby supporting single-criteria decisions as well.

early design decision. However, it must be noted that applying the approach to the decision brings along additional efforts for the design team, that must be accommodated in the early phases. As for not impacting or constraining other, unrelated design activities, the approach is based on isolating design decision moments from the design process, supporting (and hence impacting) only the actual decision at hand.

Overall, the approach replaces selection of energy saving building based on intuition and analogy with more rational decision-making rules that allow maximal use of building performance assessment efforts. The steps that make up the procedure render the selection procedure rigorous and transparent, while the subjective elements of the decision become explicit, which makes them more accessible in the debate within the design team and between design team and principal.

4.3. Discussion and Conclusion

The main goal of this chapter is to develop an approach for well-founded selection of energy saving building components. In order to reach this goal, the requirements for making a well-founded choice have been analyzed, and existing theories for making a design decisions (like the selection of energy saving building components) have been assessed. Using elements from existing theories, an approach for performance-based selection of energy saving building components has been developed. The approach has been applied to an example and has been evaluated for meeting the requirements for a well-founded choice.

The research steps described in this chapter result in the following conclusions:

- There is a body of knowledge that addresses the making of well-founded design choices (existing of the theory on rational design decision-making (paragraph 2.1.2.), concurrent engineering, integrated product development, value engineering etc). However, all of this knowledge is rather general. It is applicable to different engineering domains and across different life-cycle stages of the engineering systems concerned. Since the knowledge is of general applicability it provides useful elements for a well-founded selection of energy saving building components, but does not include a clear roadmap or step-by-step plan for the selection of these elements.
- Elements from the existing body of knowledge can be used to develop an approach for a well-founded selection of energy saving building components. This approach consists of the following main steps:
    1. Definition of an option space, that identifies which combinations of a given building design with one or more energy saving building components are to be considered.
    2. Identification of the relevant functions of all design options, in order to find the relevant criteria for the selection.
    3. Specification of performance indicators, objectives, requirements and constraints.
    4. Prediction of the performance of all design options, for all performance indicators, through execution of (virtual) experiments using building performance assessment tools.
    5. Evaluation of predicted performance, in which a subjective assessment is made of how well each design option performs each individual function, and where a tradeoff between the performance of different functions can be made as well (for instance by applying an additive utility function).
- The approach as developed in this chapter improves the decision-making process on selection of energy saving building components from heuristic search to a partial search

that finds the best option out of a given option space. Though the creation of a set of different building design options that include energy saving building components is still dependent on experience, the selection from that option space is rationalized. In the approach, energy saving components will be selected from a well-defined list of alternatives. Selection will be based on clear criteria, using objective (reproducible) performance prediction methods, and subjective values will be made explicit, allowing discussion of these values between architect, consultant and principal. The approach also ensures that relevant performance aspects are identified and that the building performance for those aspects is assessed, resulting in a multi-criteria decision; it can be applied during all phases of the building design process, including the early phases. Since it only considers the selection of energy saving building components at a specific design decision moment it does not hinder unrelated design activities.

- In the approach the use of performance analysis tools to predict building performance is an essential part of the preparation of the selection of energy saving building components.

Remarks:
Based on the importance given in this thesis to the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, an explicit choice has been made to apply existing knowledge to this problem and to develop a general, universal approach for the selection of these components.
Another possible line of research would be to make a concise model-based, comprehensive study of all aspects that need to be considered when selecting specific energy saving building components from a finite set (for instance from a set of design alternatives that includes a heat pump, cogeneration unit and PV). Such a study will reveal the different performance aspects that need to be considered in the specific case. It will provide deep, component-specific insights in the elements of specific decision problems; it will result in a well-supported view on competing energy saving components and all associated relevant performance aspects, usable performance indicators, and will give detailed information on the required performance information that is needed to compare the competing components, allowing to assess the suitability of existing computational tools to generate that specific information. Some feeling for this type of research can be obtained from the example in section 4.2.2. However, there is a need for more comprehensive research efforts along these lines that will contribute new insights to the groundwork presented here. The knowledge obtained from such studies will be of direct use for design decisions that involve the energy saving components that have been studied in depth.

5. Tools to Support the Selection of Energy Saving Building Components

"Steel can be any shape you want if you are skilled enough, and any shape but *the one you want if you are not."*

(Robert M. Pirsig)

Chapter three revealed that in current building design projects computational tools are not used to support the selection of energy saving building components. It also found that in these projects the selection of energy saving building components mainly takes place in an intuitive manner, based on earlier use of the same components in previous buildings and in analogy with demonstration projects. It was concluded that both the selection procedure of these components, as well as the tools that support that procedure need to be addressed. Chapter four therefore dealt with making well-founded choices, and developed an approach for performance-based selection of energy saving components.

This chapter deals with tools that support the selection procedure for energy saving building components. The main goal is to assess the adequacy of existing tools in providing support for the selection of energy saving building components, and to identify possibilities to improve existing and future tools. In doing so, it addresses the research questions on adequacy of existing tools, expected effects from ongoing tool development and integration efforts, and about options to improve tools (see 2.5). Some of the ideas on improving tools that are developed in this chapter will form the basis for the strategy and prototype development that is presented in chapter six.

In order to reach the goal, three research questions need to be answered:

- what are the requirements for tools that are to support a well-founded selection of energy saving building components?
- how adequate are existing tools when it comes to fulfilling these requirements?
- how can existing tools be improved, in order to better support the selection of energy saving building components?

In order to answer these research questions the following research steps have been taken: analysis of the different main categories of tools and their role in supporting the selection of energy saving building components, and assessment of existing tools and possibilities for improvement of the two most important categories: analysis tools and support environments (van der Voorden *et al.*, 2001; de Wilde and van der Voorden, 2003a).
The analysis of the main categories of tools, which is described in paragraph 5.1, consists of:

- an overview of the main categories of tools that can be discerned;
- analysis of the roles that these categories of tools can play in order to support the selection of energy saving building components.

Analysis tools are the subject of paragraph 5.2.; specific requirements for supporting the selection of energy saving building components for this category of tools will be identified, allowing:

- assessment of the adequacy of existing analysis tools (paragraph 5.2.1.);
- development of ideas on how to improve analysis tools (paragraph 5.2.2.).

Support environments are the subject of paragraph 5.3.; specific requirements for supporting the selection of energy saving building components for this category of tools will be identified, allowing:

- assessment of the adequacy of existing support environments (paragraph 5.3.1.);
- development of ideas on how to improve support environments (paragraph 5.3.2.).

Paragraph 5.4 concludes the chapter by summarizing the results of this chapter, and by presenting conclusions and remarks.

5.1. Overview of Existing Categories of Tools

When it comes to supporting the selection of energy saving building components many different categories of tools can play a role. Hendricx (2000) discerns three main categories of tools: modeling tools, design tools and analysis tools. Modeling tools help to represent (draw, render, view) a design, design tools help to generate new design alternatives/options/variants, and analysis tools analyze specific aspects of a given design[26]. While this provides a good handle to start a discussion of tools, further extension is needed when it comes to analysis of support for the selection of energy saving building components.

First of all, the three categories of Hendricx do not cover a number of other tools: process/planning tools, communication tools and tools used during building construction for instance are not covered by the framework. Secondly, it is important to note that tools can be embedded in support environments. Support environments provide functionalities that support the use of other tools, such as easy access through (standardized) interfaces to embedded tools, coupling of tools, use of shared information repositories, etc. The extended framework that results from these issues is depicted in figure 5.1.

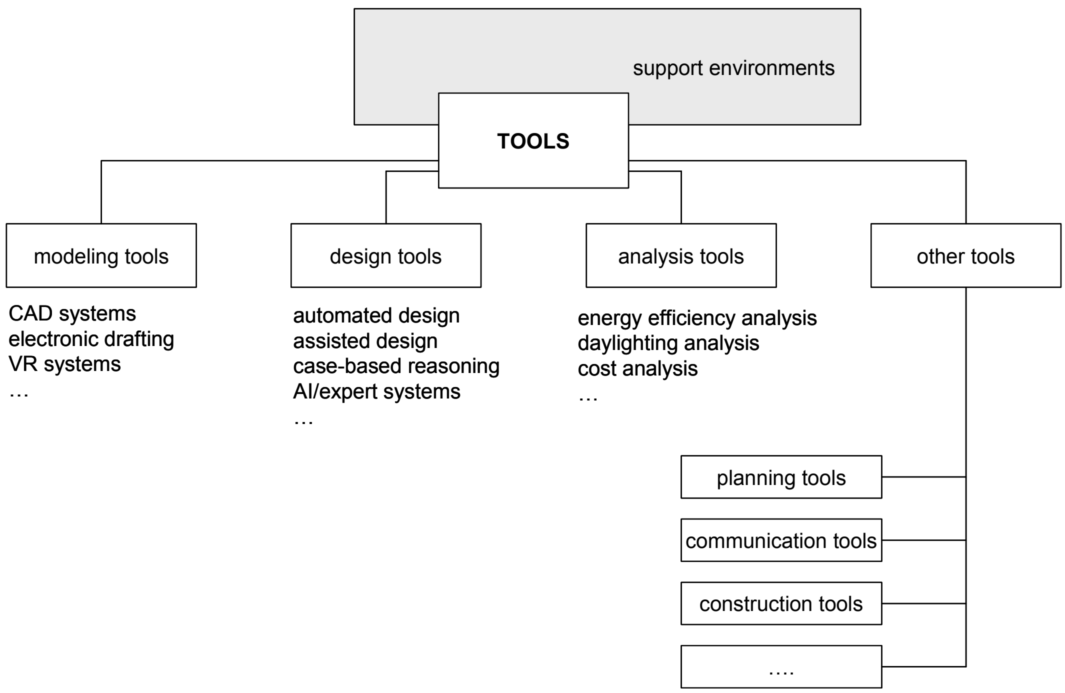


Figure 5.1: General overview of different categories of tools

[26] These three categories of tools are described in more detail in paragraph 1.1.

Note that this definition of categories of tools is based on a design-based point of view. Other classifications are possible as well, for instance according to underlying enabling technologies and discerning computational tools, database systems, geometric representation tools, spreadsheet applications, text processors etc.

Within the different categories a huge number of individual tools is available that all can be used in building design projects. These existing tools are constantly being updated and improved. The largest number of tools can be found in the category of analysis tools; for instance for the issue of building energy alone, the US Department of Energy building energy software tools directory on the internet (DOE, 2002) lists more than 200 tools. In the category of modeling tools there is a smaller number of tools, but these tools all enjoy a broad uptake in architectural practice – almost every building design project now uses these tools to describe the building design. Some well-known tools in this category include AutoCAD (Autodesk, 2003), Archicad (Graphisoft, 2003), Microstation (Bentley Systems, 2003) and SoftCAD (SoftCAD International, 2003). Development of CAD tools continue at a rapid pace, see e.g. Husin and Rafi (2003). In general, the category of design tools appears to be less developed; however, it is hard to give a conclusive overview of all existing tools in this field because of the large number of design options and aspects. On the one hand work in the field of case-based reasoning, artificial intelligence and expert systems target this category, but the resulting tools do not seem to have reached building design practice yet. On the other hand electronic product catalogues, must notably the Sweet's catalogue (McGraw Hill Construction, 2003) can very well be used as design tool. It is interesting to note that when focusing on energy design tools, a close examination reveals that most tools that are described as energy design tools actually are energy analysis tools in the sense of the categories as described in this paragraph; only very few of those tools actually suggest design alternatives, one notable exception being Energy-10 (Balcomb, 1997). Other tools like communication tools (email programs, web based data exchange tools etc, planning tools, construction tools etc are widely available. Since this is a very general group no further discussion is provided here; in chapter six some selected tools in this category will be discussed in the context of prototype development.
Support environments that include different categories of embedded tools are still in a development phase; see for instance the ongoing work on the common product model in the IAI-IFC (International Alliance for Interoperability, 2002) and the environments under development like SEMPER (Mahdavi, 1999) and the Building Design Advisor (Papamichael, 1999).

To analyze the adequacy of these different categories of tools for the selection of energy saving building components, their functionality has been compared with the information required during the different steps of the approach for selection of energy saving building components as developed in chapter four[27].

- *Development of an option space:*
  For this step information is needed on which energy saving building components might be appropriate for a specific building design. Such information calls for a specific design tool. Note that the approach as described in chapter four assumes that the members of the design team define the option space using their expertise; from this point of view a design assisted paradigm rather than an automated design paradigm is the preferred option. The design tool must provide an overview of existing energy saving building components and the functions of these components, where the functions needed by the building design can

[27] See 4.3.2. for a detailed description of the approach.

be matched to functions provided by energy saving building components. The overview of components and functions can be stored in a database system, and identification of components with matching functions can take place using a query function. For capturing the option space modeling tools can be used; however, modeling tools do not actually provide information needed within the selection process[28].

- *Identification of relevant functions:*
  For this step information on the functions assigned to a building design as well as on the functions provided by energy saving building components is needed. In order to access the functions that a building design can fulfill an overview of possible building functions and sub-functions can be used; since this is static information, this can be easily stored in a database. Similarly the functions provided by energy saving building components can be analyzed and stored in a database; this can be the same database that is used in the previous step. Since the information is stored and retrieved when needed this cannot be considered to be a design, analysis or modeling tool. A spreadsheet with this information can be added in the category of 'other tools' and accessed via a support environment.
- *Specification of performance indicators, objectives, requirements, constraints:*
  For each function that is identified in the two previous steps, further information is needed on possible performance indicators[29] that can be used to assess the fulfillment of these functions, as well as common limiting values for these performance indicators (objectives, requirements and constraints). This is again a discrete set of possible options (performance indicators and their range) that can be added to a database system or spreadsheet in the category of 'other tools' and accessed via a support environment.
- *Prediction of performance:*
  The information that is needed in this step is highly variable, since it depends on the building design options that are to be assessed, and the performance indicators selected to quantify performance of these options. Due to the infinite number of building design options that can be defined and the large number of performance indicators that can be selected for assessment, this information needs to be generated during the building design process through the use of (building performance) analysis tools.
- *Evaluation and selection:*
  For the final step of evaluation and selection information is needed on subjective values used by the decision makers (design team). This information cannot be pre-defined, but can be easily inserted in a spreadsheet application that also contains data on performance of all building design options and which helps to apply evaluation and decision making rules. Such decision support tools would again be considered to reside in the category of 'other tools', accessible via a support environment.

In addition to these information requirements, planning tools can help to support the adherence to the different steps that make up the approach. While they do not provide information that is needed for the selection itself, their inclusion in a support environment would be advantageous. The same goes for communication tools, which can play a role in information exchange between design team members during the selection procedure.

From this analysis of information requirements and roles of tools it is concluded that providing information on building performance is the most difficult part of supporting the

[28] Note that there are authors (.e.g. Yannas, 2003; Mahdavi, 2003) who suggest that analysis tools can also play a role in inspiring design. In this case analysis results are used as source of inspiration to develop new design options

[29] Where possible it makes sense to try to make maximal use of performance indicators that are also used in building codes (like the Dutch EP coefficient), since values for those performance indicators will have to be provided anyway.

approach for selection of energy saving building components, since performance information depends on the building design in question and needs to be generated during the building design process. Analysis tools play a key role in generating this information and therefore will be discussed in more detail in paragraph 5.2.
On the other hand, it is clear that the development of a support environment can provide many useful functions that support the selection of energy saving building components. Even if a set of perfect analysis tools would be available, there are still is a need to provide a link between such perfect tools and the building design process. Therefore support environments will be discussed in more detail in paragraph 5.3.

5.2. Analysis Tools

The category of analysis tools itself can be subdivided, since there are different types of analysis. First of all one can distinguish tools that analyze building (design) properties and tools that analyze building (design) performance. Properties are characteristics of the building or building design that are set down with the building design itself, like for instance the floor area, internal volume etc. Performance is related to the building function; performance results from the interaction of building properties and building usage, like for instance energy efficiency or seating capacity (in the first case depending on interaction of thermal properties of building and HVAC-system with the climate, internal use etc, and in the second case depending on seating area of benches and area allocated per person). The category of performance analysis tools can be subdivided in a set of tools that analyze dynamic performance aspects (for instance indoor air quality) and a set of tools that analyze static performance aspects (for instance the seating capacity). Building simulation tools are tools for analyzing building behavior, and hence are synonymous with tools for analyzing dynamic performance aspects. Note that property analysis is often part of performance analysis, like obtaining the building volume as part of building energy efficiency analysis. Property analysis like U-value calculation can both be used to obtain an independent property value, or can be used in the context of a dynamic thermal analysis as well. See figure 5.2.

Finding an applicable analysis tool that provides the specific information needed in a specific design process to support the selection of energy saving building components can be complicated. The information generated by the tool has to match the specific information requirement at that time (e.g. performance information on energy efficiency, thermal comfort, etc.) and must be applicable to specific building design options in question (e.g. an office building with either photovoltaic arrays, a double façade or a co-generation unit). Once a suitable tool has been found, runs have to be executed for the different design options. In general this requires physical modeling and/or simplification, and specification of model parameters, computational settings, and options for output generation and post-processing. All these efforts must fit within the metrics of the building design process, which in the case of support for the selection of energy saving building components means that tools must be used in the early phases of the building design process (where the building design often still is conceptual and not all properties of the building are known).

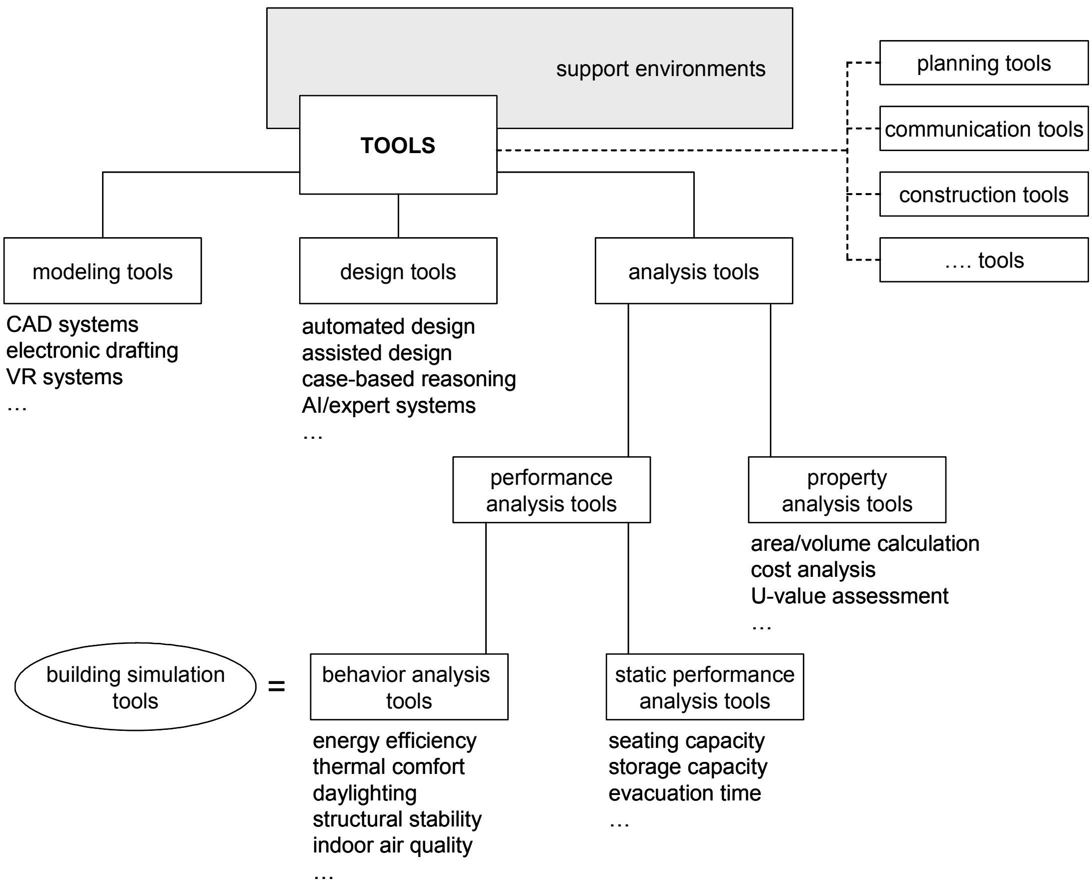


Figure 5.2: Sub-categories of analysis tools

5.2.1. Assessment of Existing Analysis Tools

Analysis tools that are to support the selection of energy saving building components must provide relevant information that supports the step of building performance prediction. However, they must also be usable during the building design process. Therefore they must meet the following requirements, concerning both information content as well as operational issues:

Requirement 1: analysis tools must be able to accommodate the specific building design alternatives (building and energy saving components) that are considered during the selection process. This is not a trivial issue, since many tools are limited in the building design characteristics and components that can be accommodated.

Requirement 2: analysis tools must provide the specific information that is needed for the selection process. They must be able to carry out the virtual experiments that have been defined, returning either building properties or requested performance indicator values (or generating data from which these performance indicator values can be easily derived). Relevant dynamic performance aspects for the selection of energy saving building components are energy efficiency and thermal comfort; yet there are many ways to quantify these performances, and the choice of the appropriate experiment for a given design context should be left to the design team and not be imposed by the analysis tool.

Requirement 3: analysis tools must be able to provide the requested information rapidly, without halting the design process for extended periods; if information generation takes too long there is a risk that the design process will continue without waiting for the information that is being generated.[30]

Requirement 4: analysis tools that support the selection of energy saving building components must be applicable during early design phases (feasibility study, conceptual design), as it is here that most components are being selected.

Since there are large numbers of analysis tools it is not possible to do an in-depth analysis of the adequacy of all existing individual tools in the light of these requirements. Therefore the assessment will focus on a specific sub-category of analysis tools that is essential when it comes to selecting energy saving building components: tools that can be used to analyze the energy efficiency of whole buildings. As this sub-category still contains a large number of tools (US Department of Energy, 2002a), the assessment will be carried out in two steps:

1. A representative set of typical building energy analysis tools will be assessed using descriptions of these tools. Tools to be reviewed rank among the most widely used tools, or are among the tools that are frequently discussed in literature on tools for building energy analysis.
2. In order to obtain further insights into the adequacy to support selection of energy saving building components the actual hands-on application of one exemplary analysis tool as support instrument for the approach to select energy saving building components will be discussed, using the example presented in paragraph 4.2.2. as design context.

Description-based assessment:

From detailed descriptions, both by the authors of these tools and from the building energy software tools directory on the internet (US Department of Energy, 2002a), the usability of the following tools[31] (presented in alphabetical order) has been studied[32]: Building Design Advisor (Lawrence Berkely National Laboratory, 2002a); Energy-10 (Lawrence Berkely National Laboratory, 2002b); Capsol (Physibel, 2002), EnergyPlus (US Department of Energy, 2002b), ESP-r (Energy Systems Research Unit, 2002), IDA-ICE (Equa, 2002), Matlab/Simulink (MathWorks, 2002), TRNSYS (Solar Energy Laboratory, 2002) and VA114 (VABI, 1993). Descriptions of these tools are provided in appendix B; here only some essentials are mentioned.

[30] Regarding requirement 3, it must be observed that if performance analysis is moved forward in the design process (from a later phase to an earlier phase, e.g. from final design to conceptual design), then the earlier phase should be allowed to take more time to compensate for the additional activities. Moreover, if new or additional activities are added to the design process that increase the quality of the building design, there is a reason to allow more time for the overall design process (if needed).

[31] The version of the building energy software tools directory dated 8 November 2001 (DOE, 2002; accessed 4 July 2002) lists 240 tools; of these, 76 tools are able to simulate whole buildings. According to their description in the tool directory, 25 of these tools are able to do dynamic building simulation of both energy flows and temperatures. These 25 tools vary between academic (e.g. ESP-r) and commercial software (e.g. TRNSYS); they require different levels of computer literacy. The seven tools discussed here are the most widely used tools of this shortlist.

[32] Energy-10 and Building Design Advisor (BDA) are tools that rely on other embedded tools for analysis tasks. Because of this fact Energy-10 and BDA will also be discusses in paragraph 5.3. on support environments

- Building Design Advisor

  The Building Design Advisor (BDA) is a platform that combines several software modules that are relevant for building performance analysis and building design. Though being intended to be a tool to support design decision making in practice, it has not yet seen widespread use.

  Regarding the capabilities of the BDA to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

  1. The BDA can accommodate those option spaces that can be handled by the analysis modules. The current version therefore can be used to assess the buildings and energy saving components that can be accommodated in the daylighting computation module, the electric lighting module, and the DOE-2 simulation engine. Describing these designs can be supported by using the BDA databases/libraries.
  2. From literature it appears that (although operational conditions can be modified by the user) the building analysis in the BDA is predefined, allowing all building design variants described to the BDA to be evaluated and represented in the decision desktop in the same manner. In other words: there probably is only limited room to make the BDA predict building performance in the metrics of the specific performance indicators (modify the simulation experiment to meet the situation at hand).
  3. Because of the default selector in the BDA, the BDA can be employed rapidly. However, the speed of the computations performed with the BDA depends on the speed of its components; for thermal simulation, the BDA is therefore just as fast as traditional DOE-2 simulations.
  4. The same default selector makes the BDA suitable for use in early design stages, when not all details of a building are available.

- Energy-10

  Energy-10 is a design tool for architects and engineers, that analyzes energy consumption of buildings consisting of either one or two zones. Development of building models can be highly automated, and evaluation is very fast. Results are ranked based on energy performance and compared to a base-case. Energy-10 relies on an embedded simulation tool for actual simulation work.

  Regarding the capabilities of Energy-10 to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

  1. Energy-10 only accommodates building that can be modeled as one or two zones. Various energy-efficient strategies can then be applied to the building that bring in energy saving building components with default properties and settings. However, describing specific design options is much harder; this requires defaults to be manually changed. The set of energy-efficient strategies does not yet include all energy saving components.
  2. Energy-10 only provides feedback on energy consumption (for heating, cooling and lighting). Thermal comfort is not evaluated, nor is there any chance to make Energy-10 adhere to specific experimental conditions other than those governed by modifiable parameters. The ranking mechanism does not seem to add real important information – especially since Energy-10 produces a one-criteria evaluation only.
  3. Energy-10 is extremely fast in doing hourly simulations.
  4. Because of the easy building model development, Energy-10 is very well suited to be used during early phases of the building design process.

- Capsol
  Capsol is a commercial multi-zone transient heat transfer simulation program for the evaluation of heating, cooling, overheating, sunscreens and passive solar energy. Regarding the capabilities of Capsol to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:
  1. Capsol can perfectly accommodate option spaces that are based on architectural variation. It is not intended to analyze HVAC-systems, so HVAC-related energy saving building components are more difficult to simulate.
  2. Capsol has an extensive set of options to generate thermal performance data according to user preferences.
  3. Capsol does not require programming efforts to do simulations, describing a simulation is straightforward. Calculation times are state-of-the-art, allowing the simulation of a multi-zonal building (including HVAC systems etc) for a full reference year with hourly climate data in a timeframe of minutes.
  4. Capsol is intended to be applicable in all phases of the building design process. It is applicable during early phases, provided that the user can model the building and enter appropriate (default?) values that are needed for the simulation.

  Note that Capsol has also been used to gather hands-on assessment of the application of building performance simulation tools to support the procedure for selection of energy saving building components, see paragraph 5.2.2.

- EnergyPlus
  EnergyPlus is a major building simulation tool that is based on two predecessors, BLAST and DOE-2. EnergyPlus is still under development.
  Regarding the capabilities of EnergyPlus to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:
  1. EnergyPlus supports an extensive set of options regarding both architectural and HVAC-components. Components that are not yet available can be expected to be developed in the near future. Note that EnergyPlus benefits from the many component models in BLAST and DOE-2, that all can be converted to EnergyPlus.
  2. EnergyPlus has a large set of user-definable output formats, not only including energy use and thermal comfort, but also reporting on daylighting, electrical power production/use (PV) etc.
  3. Application of EnergyPlus is not rapid; modeling design options in this tool is quite an effort. The actual simulations have a run-time that is equivalent to that of similar tools.
  4. The applicability of EnergyPlus to early design phases depends entirely on the capabilities of the users to develop corresponding building models in this tool. Overall however, the feeling is that EnergyPlus is more geared towards evaluation of later design stages.

- ESP-r
  ESP-r is a dynamic thermal simulation program for the analysis of energy and mass flow problems within the built environment. ESP-r is used extensively in both building research and in energy/HVAC consultancy. Over the years many modules have been added to the tool, giving it many additional capabilities. Regarding the capabilities of ESP-r to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

1. ESP-r already accommodates a large combination of buildings and energy saving components. Where no pre-defined components are available, there are many users and developers that are able to add components to this tool.
2. ESP-r allows many user-defined performance predictions; in fact, the tool is probably one of the most versatile options regarding energy, daylighting, CFD, and complex control system simulation. However, this comes at a price: making ESP-r generate exactly the required performance prediction requires a high programming literacy.
3. Deployment of ESP-r in general is not rapid. A special ESP-r application, the Project Manager (Hand, 1998) has been developed to make ESP-r usable as a support instrument in the building design process. As described by Hand (1998, page 84) 'The Project Manager is an application which controls the process of simulation from the initial planning, through the phases of description, simulation, assessment and reporting…The principal aim is to hide complexity by arranging for a single point of problem definition and evolution and a single simulator which can recognize partial problems and act accordingly'. This Project Manager application has been used in a number of demonstration cases, yet independent reports of its use have not yet been obtained.
4. Depending on the capabilities of the users to develop corresponding building models in this tool, ESP-r can be used in all design phases. Overall however, the feeling is that ESP-r is more geared towards evaluation of later design stages. Again, the Project Manager application (Hand, 1998) might improve things, but certainly has not yet achieved a breakthrough.

- IDA-ICE

  IDA is a general purpose simulation environment for modeling and simulation of modular systems. A version dedicated to the simulation of thermal comfort, indoor air quality and energy consumption named IDA-ICE (Indoor Climate and Energy) is commercially available; this is mainly used by HVAC-designers and consultants, but also for other purposes like education and building research.

  Regarding the capabilities of IDA-ICE to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

  1. IDA-ICE is geared towards architectural (e.g. atria) and specifically HVAC-related energy saving building components.
  2. Because of its embedding in a general simulation environment, IDA-ICE allows to obtain specific, tailor-made performance predictions; however, this requires expertise to work with the general IDA-tool.
  3. IDA-ICE can be deployed rapidly, in a robust manner with an attractive but solid drag-and-drop interface on component level.
  4. IDA-ICE seems to be more suitable for use during later phases of the design process, where much information on component-level is available. IDA-ICE is tailored towards HVAC-design, which currently often takes place during later phases.

- Matlab/Simulink

  Matlab is a general computing and analysis environment used by engineers worldwide, in all kinds of domains. Simulink allows modeling, simulation and analysis of dynamic systems. Some research institutes and universities have used these tools to do building performance simulation.

Regarding the capabilities of Matlab/Simulink to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

1. Basically any system can be analyzed using Matlab/Simulink; however, a complete modeling effort (from problem description to development of mathematical equations) will be required, since other models are not easily obtained.
2. Matlab/Simulink will allow all kinds of performance predictions, but again at the cost of a complete modeling effort.
3. Because of the need to do all modeling, Matlab/Simulink is not rapidly applicable to building analysis problems.
4. Matlab/Simulink can assess building designs in all stages, once described to the system.

- TRNSYS

  TRNSYS is one of the most well-known thermal simulation tools. It is based on a modular approach. It is a program that went through years of development; it comes with an extensive set of (mainly HVAC) components.

  Regarding the capabilities of TRNSYS to provide computational support for the procedure for selection of energy saving building components, the following observations have been made:

  1. TRNSYS is very suited to evaluate buildings with HVAC-oriented energy saving building components; however, the program is less friendly when it comes to simulate more architectural building features. However, virtually any building design or building component can be analyzed by developing new, applicable component modules.
  2. TRNSYS allows an extensive set of thermal performance predictions.
  3. TRNSYS can be deployed relatively rapidly if the required component modules are available.
  4. TRNSYS can be used in early phases if sufficient building design information is available, or default values for the TRNSYS components can be used. Modeling conceptual buildings is more difficult with this tool.

- VA114

  VA114 is a simulation tool that is widely used in the Netherlands; for instance this tool has been used in two of the case studies described in chapter three. VA114 comes in different versions. This description bases itself on the 1993 version, but also notes some new developments. The 1993 version of VA114 is mainly intended to assess thermal behavior of office buildings, focusing on the typical lay-out of a corridor with office cells on each side.

  1. VA114 allows direct assessment of office buildings with typical HVAC-systems; other energy building saving components and features can be incorporated by running separate calculations and linking the results to the VA114 simulation. However, the new version of VA114 that is currently under development will incorporate 'specialties': specific building systems like energy saving building components are now being added.
  2. VA114 provides detailed performance information on heating and cooling loads, as well as thermal comfort in the building. For this latest performance aspect the tool calculates weighted degree hours, which is used frequently to specify performance requirements in Dutch office buildings and contributes to the popularity of the tool in the Netherlands.

3. VA114 can be deployed rapidly if the building under assessment closely fits in the intended building class; other buildings require more modeling efforts and expertise, especially if the aim is to incorporate additional features. Note that further support for this aspect is under development as well. For instance, an additional modeling tool assisting complex geometry input is available through the 'uniform modeling environment'.
4. VA114 can be used in early phases, as long as the user can model the building and enter appropriate (default?) values that are needed for the simulation.

The company VABI that develops VA114 is also involved in other efforts to support design support. While not directly focused on the selection of energy saving building components and therefore not discussed in more detail, two efforts are noteworthy: the work on an interface named Orca to VA114 that helps architects to consider thermal comfort aspects (van Dijk, 2001) and the efforts in cooperation with Deerns Consultants on a design tool named h.e.n.k. that is intended to do simulations with only limited input data during schematic building design (Itard, 2003).

The overall finding from the description-based review is that the main thermal building simulation tools like Capsol, EnergyPlus, ESP-r, IDA-ICE and TRNSYS and VA114 are all capable of supporting the selection of energy saving building components, on condition that enough time is available to do the required (and mostly very specific!) modeling and simulation work.
Further information on the adequacy of these tools is obtained by actual hands-on application of one exemplary analysis too, Capsol, which has been used as support instrument for the selection of energy saving building components in the example presented in paragraph 4.2.2.

The design context presented in paragraph 4.2.2. required the prediction of heating and cooling loads per year, hourly temperatures in different building zones, and hourly power production by PV modules. Capsol was used to support a rational selection of one design option from an option space containing five alternatives (building 'as-is', building with isolated sunspace, building with sunspace for ventilation pre-heating, building with polycrystalline PV and building with amorphous PV). For these five options, five performance indicators have been specified: energy-efficiency, thermal comfort, embodied energy in producing the building, additional useful space, and electrical power self-sufficiency. Capsol was used to obtain heating/cooling loads for the first performance indicator, hourly average air temperatures for specific building zones for the second and fourth indicator, and hourly irradiation of surfaces for the fifth indicator.

In order to obtain this information the following main information had to be put in input-files for the program: building design description (number of zones, volume of zones, wall types including details on layers, thickness and properties, walls data with information like area and heat transfer coefficients, orientations and slopes, connections between zones and walls, heating equipment, cooling equipment and sunshading equipment), test conditions (climate, set point values and operating regime of climate control systems, internal heat loads), calculations settings (time step, simulation period) and a specification of the required output data (specification of type of information, frequency, statistical function, scope days). For each of the five options the input-file was modified to reflect the specific situation, after which a dynamic simulation was run. Relevant data, presented by Capsol as an ASCI-file, was then manually collected and processed to produce the required performance indicator values.

Regarding the four requirements the following additional insights have been obtained:

1. Requirement 1 (accommodation of a specific option space):
   Capsol accommodates an option space as given in the example, including energy saving building components. However, the building design had to be simplified in order to get a manageable model in Capsol. For instance, instead of entering all 22 offices, 2 corridors, reception and coffee corner, only 5 zones were used. Similar efforts were needed for the façade, sunspace and PV-arrays. This modeling task requires expert user intervention and cannot be automated.
2. Requirement 2 (performance prediction that is relevant for the design decision):
   Capsol is fully capable to provide the data that is needed to derive performance indicator values. Yet it does not often return performance indicator values directly, requiring user intervention to calculate these from raw data. This in spite of the fact that Capsol has an extensive menu to specify the alphanumeric output one wants to generate. The main reason Capsol does not return performance indicator values is that the virtual experiment conducted during simulation is still open to user definition; therefore, only observable states can be predefined as output.
3. Requirement 3 (rapid analysis of performance):
   The simulation effort required a full-time effort of two working days in order to obtain and roughly check results. This in spite of ample previous experience with Capsol and the availability of completely specified building design options and specific performance indicators. This time is needed mainly for modeling of the building and the test conditions to match the design options and performance indicator specifications. Because of this, tools like Capsol are not really rapid performance assessment tools; a careful simulation procedure takes time (of course, depending on the complexity of design and required data).
4. Requirement 4 (applicability during early design phases):
   There is no reason to believe that tools like Capsol cannot be used in early design phases. As long as there is enough time allowance for identification of the main features of the building design and representation of these features in a suitable model, which requires expert intervention, performance prediction is possible[33].

The experience from hands-on application confirms that modeling efforts are the key to success when tools are to support the selection of energy saving building components. Modeling plays a role in getting tools to accommodate a specific option space, providing a performance prediction as required, the speed of the whole simulation effort, and applicability during early phases.

5.2.2. Improvement of Analysis Tools

From the assessment of existing analysis tools it is clear that these tools can play an important role in the selection of energy saving building components and, broader, in building design. But there also is room for improvement, especially regarding modeling-related aspects. These improvements will help future analysis tools (both new versions of existing tools and completely new tools) to better meet the requirements of accommodating specific option spaces, to provide a performance prediction as required, and to be fast and applicable during early phases.

[33] Note that the case as described in paragraph 4.2.2. is a design situation that is typical of the phase of conceptual building design.

The existing analysis tools are able to handle many design alternatives and to produce different types of performance information. While this makes these tools versatile it also constrains their handling, since users must know which alternatives and performance indicators are covered by a specific, individual tool, and must know how to access these features.
Improvement can be achieved by reverse-engineering of these tools, which consists of unraveling the amalgamated design alternatives and information types that a tool can capture as well as the different ways that the tool can act on this input. If this can be achieved it will become easier to select the type of analysis model (like using one model that combines convective and radiative heat transfer, or using a model that has individual detailed descriptions of both, or like combining ventilation and infiltration or treating these individually) that is relevant in a design context, provide the analysis tool (model) with all relevant data, and do a specific virtual experiment without having to worry about the modeling task. It would be helpful if analysis tools then would return performance indicator values as specified through these virtual experiments, instead of current raw performance data. Some work along these lines of thought will presented in chapter six.
Reverse-engineering of tools also impacts the speed of building simulation efforts. Acceleration of performance prediction by tools currently no longer depends on the speed of the actual computational procedure (run-time) only. Although full simulations of a complex building for a full hourly reference year still can claim some hours, the main barrier regarding speed now is the need to develop and test a building model and the climate conditions, HVAC-settings, occupant behavior etc assumed in that model.

Other areas that require attention are coupling of different performance domains, accuracy of computational performance prediction, and smaller, more model-related issues:

- Many current R&D projects in the field of development of performance analysis tools work on the coupling of tools in different domains, like for instance the coupling of thermal simulation tools with airflow simulation or daylighting. These efforts definitely are relevant, since this coupling is needed to study cases were both fields interact. It would be even more advantageous if a standardized way could be developed that allows easy coupling and de-coupling of tools for different interrelating domains, giving the user full control of what kind of aspects and interactions are to be studied in a specific case. It is important to realize that one big simulation tool that is able to deal with all relevant performance aspects of all possible buildings is still far away. But even if such a tool could be developed, one still would want to be able to turn aspect simulations on and off at will.
- Another issue for future development is accuracy of building simulation. This could take the form of add-on modules to tools that indicate accuracy of computational results. Even better would be the option to provide the user with an analysis of expected uncertainty before simulating building behavior; such information would allow the user to select a building model that balances the information need of the model with his requirements regarding the accuracy of the results. Such modules might one day allow accuracy management.
- On a different level, the simulation of more complex geometries is still not very easy in current thermal simulation tools. Most tools assume box-like internal spaces that are all situated on floors of the building, making it difficult to simulate more expressive floor plans and spaces like staircases or atria with stack effects or stratification. Also a more focused use of existing, general data formats (like for instance TRY or TMY2 climate data) would be beneficial for both climate data and material data, since many tools still

require this information in specific native formats, requiring the user to maintain tool-specific libraries with such data. Also, it would be beneficial for the usability of existing tools if they all include idealized HVAC-systems (in other words, allowing the user to select an idealized HVAC-system that provides heating and cooling power as required, without any upper limit, time constraints etc).

5.3. Support Environments

Support environments have been defined in paragraph 5.1 as tools that provide functionalities that support the use of other tools. These environments are still in a development phase, and therefore can take many forms. However, the fact that one tool that allows to assess all relevant performance aspects is still far beyond reach results in a need to develop robust simulation environments that manage the interaction between various tools, and give users a uniform way to access these tools[34]. An overview of common elements of support environments and relations with external tools is shown in figure 5.3.

Common elements in support environments are a module that communicates with the user, and a module that controls the embedded tools. These tools need to be provided with information, using a data exchange module that manages information flows between user, databases and between different embedded tools. Apart from this the more complicated environments need a module that controls and reports the status of the environment. Complicated environments also need to take care of consistency (for instance ensuring that design modifications made with one of the embedded tools are updated with the other tools as well).

Support environments can have links to all possible tools. Obvious connections are links with modeling tools, design tools and analysis tools. All other tools, like process support tools, decision support tools, communication tools, optimization routines etc can also be included. It also makes sense to link a support environment with common databases, providing a consistent source of information on material properties, weather data etc. Another logical addition is that of a common design description (product model) that stores all available information on a building design that is under development, thereby maximizing consistency. See figure 5.3.

[34] As long as assessment of uncertainty associated with the use of performance analysis tools is not a standard procedure, there is a need to use one and the same analysis tool to equivalently quantify the performance of different design options for a given performance aspect, as predicting the same performance with different tools might result in large tool-dependent differences (Lomas *et al.*, 1991; de Wit, 2001). Moreover, in the long term it might be advantageous to use the same tool during successive phases of the design process, allowing to compare the development of the predicted performance with the development of the building design, like proposed by different authors, (e.g. Morbitzer *et al.,* 2001) and without having to switch from one tool to another.

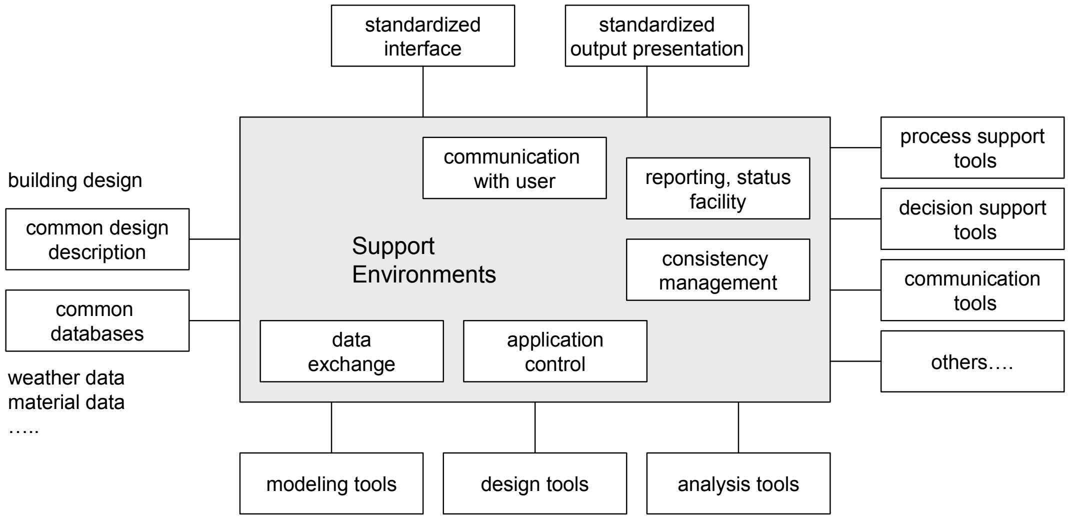


Figure 5.3: Elements of support environments

5.3.1. Assessment of Existing Support Environments

Support environments that are to enable the selection of energy saving building components must contain elements that support (parts of) the selection procedure for these components. Therefore they must meet the following requirements:

Requirement a: support environments must provide access to suitable tools for relevant steps of the selection procedure. The environment must contain a selection mechanism that determines which tool is most suitable to perform a specific task; where only one tool is present it must check whether this tool is applicable.

Requirement b: support environments must manage information exchange between their user and embedded tools. They should help the user in providing the correct information to the tool, where possible providing default values etc, while representing the output of the tool in a useful manner. Where relevant they also must take care of internal data exchange between embedded tools.

Requirement c: support environments must provide additional functions to the user when compared to the function(s) of the embedded tool(s). Environments that do not provide additional support are user interfaces rather than support environments.

Support environments are still under development; they can take many different forms. Different environments can be found that range from environments offering basically one common building geometry model (but no common full-grown building product model) that can be exported to different applications, like Virtual Environment (Integrated Environmental Solutions, 2003) and Ecotect (Square One Research, 2003), all the way to novel environments with extended building product models and completely novel analysis tools like SEMPER (Mahdavi, 1999).

This assessment will focus on a number of support environments that are relevant from a building energy analysis point of view, thereby supporting the use of existing energy analysis tools in the context of the selection of energy saving building components.

From detailed descriptions the adequacy of the following environments has been assessed (presented in alphabetical order): Building Design Advisor (Papamichael, 1999), Combine (Augenbroe, 1994; Augenbroe, 1995), Energy-10 (Balcomb, 1997), Intelligent Integrated Building Design System (Clarke and Mac Randal, 1993; Clarke *et al.*, 1995) and ESP-r Project Manager (Hand, 1998). Also the work on the International Foundation Classes (International Alliance for Interoperability, 2002) and the related BLIS-project (BLIS, 2003) will be discussed.

- Building Design Advisor
  The Building Design Advisor (BDA) is a platform that combines several software modules that are relevant for building performance analysis and building design; because of this it has also been discusses in paragraph 5.2.1. on analysis tools.
  a. The BDA provides access to a number of pre-selected tools that cover different performance domains: for thermal simulation the tool DOE-2 is embedded, for daylighting simulation and for electric lighting analysis dedicated routines (DCM and ECM) have been developed by the authors of BDA. Since there is only one tool per performance domain there is no selection mechanism to match tools to dedicated analysis tasks other than calling the tool relevant for the performance domain.
  b. BDA emphasizes communication with the user. It has an interface that allows graphical entry of basic building geometry and provides default descriptive and operational characteristics. The results are presented in a decision desktop that presents the effect of selected parameters in graphical format. Information exchange between the embedded tools is automated and hidden from the user.
  c. While the BDA allows comparison of different design alternatives in the decision desktop, the actual support functions for other tasks than input generation (default values, easy geometry handling) and performance prediction and comparison (decision desktop) are limited.

- Combine
  Combine (Computer Models for the Building Industry in Europe) was an European research project that developed a prototype for an integrated environment that linked a set of analysis tools in different domains (energy analysis, HVAC-design, lighting). The project has been described in some detail in paragraph 2.3.2.
  a. Regarding selection of embedded tools, Combine pioneered the link between analysis process and analysis tools: through the use of Project Windows a number of analysis tools could be called to support specific, predefined tasks. Yet Combine focused on maintaining the logic of the analysis process rather than on finding the best embedded tool for a specific analysis job.
  b. The exchange of design information was a core issue of the Combine project; a product model named Integrated Data Model (IDM) was developed that allowed data exchange between embedded tools.
  c. The Combine prototype provided support for the analysis tasks through a product model (IDM) and offered process support through the Project Windows, albeit all in the form of a prototype support environment only.

- Energy-10
  Energy-10 is a design tool for architects and engineers that analyzes energy consumption of buildings using an embedded analysis tool. Therefore it has also been discussed in paragraph 5.2.1. on analysis tools. Development of building models can be highly

automated, and evaluation is very fast. Results are ranked based on energy performance and compared to a base-case.

a. Energy-10 does not provide a selection mechanism for tools; only one simulation engine is embedded, that must cope with all analysis tasks.
b. Information management is a core function of Energy-10; Energy-10 has an 'autobuild' function to allow high-speed definition of simple building models using a lot of default values. Energy-efficient strategies can then be applied to this building model, again using default properties and settings. However, describing specific design options is much harder; this requires defaults to be manually changed. Output is presented in a standard format; a ranking function to order different alternatives according to one performance aspect (energy efficiency) is available.
c. Energy-10 provides support for easy modeling of buildings and energy-efficient alternatives; it can rank these alternatives automatically. Yet this support also seems to be a weakness, since it makes it more difficult to define combinations that are not pre-defined in Energy-10. The ranking mechanism is based on one criterium only and does not support multi-criteria decisions.

- Intelligent Integrated Building Design System / ESP-r Project Manager
  The IIBDS and Project Manager are both support environments developed around the ESP-r building simulation tool; the Project Manager application is a follow-up on the IIBDS. Both projects were developed in a research context, and are related to Combine. Again, more information is provided in paragraph 2.3.2.
  a. While both the IIBDS and Project Manager are linked to the ESP-r engine for any analysis work, they do provide a module that controls access to parts of the ESP-r engine by calling specific functions. Note that ESP-r is a very extended tool, allowing building energy simulation, coupling with CFD, daylighting assessment etc, necessitating the call of relevant ESP-r modules.
  b. Information exchange is based on the IDM product model as developed in Combine; a project database and integrated performance view reporting facility have been added.
  c. The IIBDS and Project Manager provide a shell for users of the ESP-r simulation tool, with components of project management, process management and others. This predefined link to ESP-r is also their limitation.

- International Foundation Classes and the BLIS-project
  Though this in itself is not a support environment, the International Foundation Classes (IFC) currently under development by the International Alliance for Interoperability IFC (Bazjanac and Crawley, 1999; International Alliance for Interoperability, 2002, Bazjanac, 2003) and the related BLIS-project (BLIS, 2003) are worth to be discussed as well. The IAI-IFC is an attempt to define one shared building product model that will allow data exchange between different computer programs in the building industry. If the IFC would indeed become a standard, this would be a common basis for future support environments. However, efforts on implementation of the IFC (e.g. van Treeck *et al*., 2003) show that there are still limits to the actual application of the common product model in practice.
  While the IFC is still under development, the BLIS (Building Lifecycle Interoperable Software) project (BLIS, 2003) already moves in that direction by breaking down the overall IFC in a number of so-called 'use cases' that target specific information exchange needs. Use cases studied so far are data exchange in the context of client briefing, architectural design, HVAC-design, cost estimation, thermal load simulation and construction management. BLIS underlines that a product model like IFC in itself cannot solve all problems related to integration of building design and building analysis, and

shows that a process context needs to be added as well, a view now also shared by the developers of the IFC itself (Bazjanac, 2003).

a. The IFC is a common product model that needs to be able to communicate with all conceivable tools. BLIS acts as a first selection mechanism; the use cases of BLIS focus towards a context-dependent data exchange. Yet while focusing the data exchange towards specific process relevant ‘views’ BLIS does not provide a way to select the best tool for a given analysis task.
b. It will be clear that information exchange is the key issue underlying all IFC and BLIS efforts. However, due to the fact that the IFC is a general product model for the building industry, IFC models need to be able to cope with all possible design information, which has the risk of rendering them very large and difficult to handle. BLIS views help to manage the size according to specific use cases.
c. While the main scope of IFC and BLIS is data exchange, they have spawned a number of other efforts that support analysis activities. One of those is the development of a tool named Metracker (formerly: Design Intent Tool) by Lawrence Berkeley National Laboratory (2003), which allows identification, tracking and documentation of performance goals and actual performance across the building life cycle.

From this assessment of a wide range of current support environments the main conclusion is that while existing environments provide access to embedded tools, manage information exchange between user and tools and between embedded tools, and provide additional support, key issues that miss from ongoing development efforts are 1. the embedding of different analysis tools in one performance domain (e.g. energy analysis), allowing to use the best tool for one specific analysis task, and 2. the absence of efforts to develop a mechanism that determines which tool is most suitable to perform a specific task.

5.3.2. Improvement of Support Environments

Future support environments should first of all target access to the wide range of tools that is available today, without imposing a small pre-selection of tools made by the developers of the support environment. More help can be provided through the development of a selection mechanism to give easy access to a suitable tool to do specific analysis tasks[35]. Overall, it seems important that support environments have a modular structure, that clearly shows which main tasks (design, analysis, modeling) are supported and which additional support is provided (decision support, process management, common data repositories, etc).

Within future support environments and the tools embedded in these environments it would be advantageous if one could have evolving building models. Evolving building models not only deal with more and more information that needs to fit in a common, general model, but also with different aspects being relevant – like having only a crude description of form in the beginning, starting with a cube, cylinder, or box, and adding relevant geometry details later on, while having a shift in focus from energy-efficiency to thermal comfort Such evolving models then could be used during successive phases of the design process, matching the specific information available as well as the interest for specific performance aspects and

[35] Regarding analysis tools that can be embedded in support environments, it is observerd that in order for these tools to fit in the development of support environments, maximal modularity of all tool elements seems imperative. The optimal support system would have modules that can deal with simulation of different performance aspects (one by one or in combination), while these simulations themselves would be modular as well, containing a number of easily accessible approaches to deal with specific performance aspects and building (sub)systems (allowing the use of different physical models and different level of detail of these models).

relevant parameters of the building design in those stages. Figure 5.4 conveys this idea in graphical format. Note that such evolving building models should be flexible in order to match individual design projects; there is no such thing as a standard building design process and hence there is no pre-arranged sequence in which these parameters need to be studied in all projects. This idea is in line with suggestions in the same direction made in Tabary (1997), who proposes tools that are based on a gradual approach, allowing to start evaluating with only little information and moving on to a higher level of detail as more information becomes available.

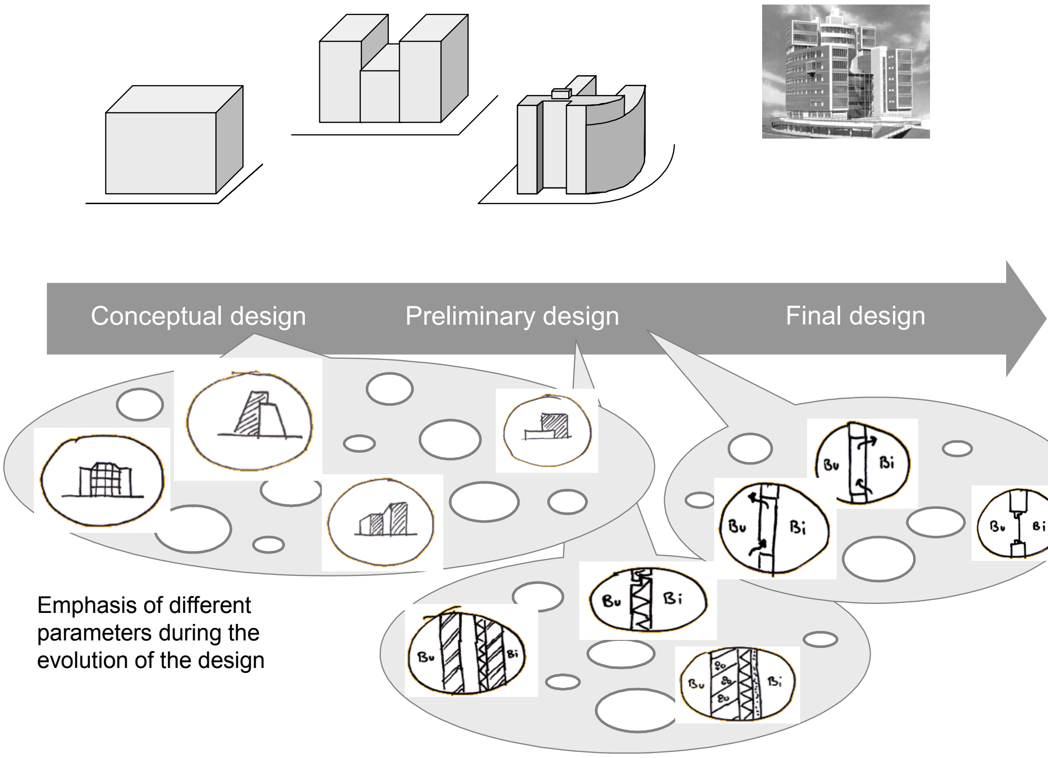


Figure 5.4: Graphical representation of different parameters being relevant in different building design phases

The principle of evolving models should combine product modeling technology as described in chapter two with a selection of tools based on relevant option spaces and performance indicators. Realization of this idea requires a deeper understanding of the relation between different performance analyses, establishing interdependency relations between energy simulation and air flow simulation (CFD), energy simulation and daylighting etc., and providing rules that make clear when a performance aspect can be analyzed in isolation and when there is a need to go to coupled simulation as described in the previous paragraph. The analysis work might even start at a stage in the design process where there is not yet any scheme, allowing the design team to assess and compare the performance of some basic lay-outs, like standard designs (reference buildings) or highly simplified schemes (like cubical models, representing heavyweight and lightweight constructions, high and low glazing percentages etc). When a set of relevant models can be developed that provides insight into the relation between specific design properties and specific building performance aspects it might even be possible to pre-analyze these models and present results in a database, much like the way first simulation results were presented to building designers. In this way, the support environment adds design support (help for the generation of building design alternatives) to strong performance analysis capabilities.

Finally, research on optimization is gathering momentum within the discipline of building simulation (e.g. Choudhary et al., 2003; Wetter and Polak, 2003; Wetter and Wright, 2003). This work can be very advantageous by providing add-on optimization routines and optimization tools that can be included in support environments rather than optimization routines that are integrated with specific simulation tools only.

5.4. Discussion and Conclusions

The main goal of this chapter is to assess the adequacy of existing tools in providing support for the selection of energy saving building components, and to identify possibilities to improve existing and future tools. In order to reach this goal, the main categories of tools and their role in supporting the selection of energy saving building components have been analyzed. For the two most important categories (analysis tools and support environments) adequacy of existing tools has been assessed and possibilities for improvement have been identified.

The research steps described in this chapter result in the following conclusions:

- There are different categories of tools that can support the selection of energy saving building components: modeling tools, design tools, analysis tools and 'others' (like process management tools, communication tools etc). All these categories of tools can be embedded in support environments that facilitate the use of individual tools by providing common and additional functionalities. Of these, the most important tools to provide support for the selection of energy saving components are analysis tools and support environments.
- Analysis tools can be subdivided in different categories; of these the category of dynamic performance analysis tools is most important.
  - Analysis tools that are to support the approach for selection of energy saving building components in ongoing building design projects must meet the following requirements: be able to accommodate specific building design options, provide the information as requested for the upcoming selection, allow rapid analysis of the relevant performance aspect, and be applicable during early design phases.
  - The main thermal building analysis tools Capsol, EnergyPlus, ESP-r, IDA-ICE, VA114 and TRNSYS are all capable of supporting the selection of energy saving building components, on condition that enough time and expertise is available to do the required (and mostly very specific) modeling and simulation work. Hands-on application of one exemplary existing thermal building simulation tool shows that these tools indeed allow analysis of the elements of specific option spaces, though modeling the building needs expert intervention. They return information on building performance that can be used to calculate performance indicator values, yet do not seem to be very tailored towards directly outputting performance indicator values. Because of the need of expert intervention to model building designs, their deployment is not really rapid; yet they are applicable in all design phases.
  - Key areas for further improvement of analysis tools include the reverse-engineering of existing tools in order to provide accurate information on the building design alternatives and performance indicators that any specific tool can handle; development of modules that provide the user with information about the accuracy of the assessment efforts; further coupling of tools in related performance domains

(including on/off control); and ongoing improvement of issues like handling of complex geometry, general data formats and idealized HVAC-systems.

- Support environments can have different forms; common elements are modules to communicate with the user, control embedded tools, and manage information exchange. Embedded tools can be modeling tools, design tools and analysis tools, as well as others.
  - Support environments that are to support the approach for selection of energy saving building components in ongoing building design projects must meet the following requirements: provide access to a suitable tool for relevant steps of the selection procedure, manage information exchange between user and embedded tools, and provide additional functions to the user when compared to the function(s) of the embedded tool(s).
  - From assessment of a wide range of current support environments (BDA, Combine, Energy-10, IIBDS, IFC/BLIS) the main conclusion is that existing environments provide access to embedded tools, manage information exchange between user and tools and between embedded tools, and provide additional support. However, these environments do not offer access to different analysis tools within one performance domain, nor a well-defined selection mechanism for tools.
  - Key issues that miss from ongoing development efforts and which should be targeted in future development of support environments are 1. the embedding of different analysis tools in one performance domain (e.g. energy analysis), allowing to use the best tool for one specific analysis task, and 2. the absence of efforts to develop a mechanism that determines which tool is most suitable to perform a specific task.
- Development of improved or even completely new simulation tools is becoming a task for dedicated research and development teams. Therefore chapter six of this thesis will focus on R&D efforts in the field of support environments, and on development of a mechanism to access (reverse-engineered) analysis tools from such an environment.

Remarks:

- As concluded from the study of literature in chapter two, the development of new building energy simulation tools shows a continuous increase of capabilities and complexity. However, this trend increases the dependency on adequate modeling and expertise, and thereby increases the barriers to integration of building design process and building simulation even further. It therefore is concluded that efforts to improve the adequacy of tools to support building design decision-making should focus at making the modeling and simulation process more transparent.
- In both the development of analysis tools and support environments there have been many efforts that aimed at facilitating modeling and simulation work by means of default values, special user interfaces that hide complexity, etc. Yet these efforts do not seem to have resulted in better integration of building simulation and building design process. The work presented in this chapter suggests that this is due to the fact that the resulting tools do not meet the requirements of to accommodating specific building design options and of providing the specific information as requested for the design decision at hand.
- It is concluded that a better alternative to simplification, hiding or automation of tool functionalities can be found in the option of subdividing tool functionalities in small but relevant modules that meet specific design analysis needs (and which can be called where needed only). However, this option requires reverse-engineering of tools to find and access these modular tools functions. This will not be an easy task: it requires rethinking

of existing building models, and analysis of the fit between these models and actual performance information needs from a design point of view.

- Since expertise will always be needed when assessing the applicability of models for specific analysis tasks, it appears to be essential that experts remain an element of building performance assessment (in other words: tools for design teams that include experts seem to have the better prospects).

6. Strategy and Prototype Development

"It was what he had been saying, only in a different language with different roots and origins. He was from another valley seeing what was in this *valley, not now as a story told by strangers but as a part of the valley he was from."*

(Robert M. Pirsig)

The previous chapters of this thesis have dealt with different aspects of computational support for the selection of energy saving building components. Chapter three analyzed the selection of these components and related use of tools in current building design projects. It was found that in current building design projects tools are not used to support the selection of energy saving building components. It was concluded that both the selection procedure of energy saving components, as well as the tools that support that procedure need to be addressed. Chapter four therefore focused on the process dimension and developed an approach for performance-based selection of components. Chapter five focused on the tools that are to support the selection. It provided an overview of existing categories of tools, and identified the categories that are most relevant when it comes to supporting the selection of energy saving building components: analysis tools and support environments. For these categories of tools chapter five analyzed the adequacy of existing tools and identified possibilities to improve existing and future tools.

This chapter deals with the feasibility of the ideas for improvement as presented in chapter four and five. The main goal here is the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, and the development of a substantiating prototype that demonstrates the feasibility of this strategy. In doing so this chapter addresses the main goal of this thesis, development of a strategy, as defined in paragraph 1.3 and answers the two remaining research questions from paragraph 2.5:

- How can improvements of the way of selecting energy saving building components and improvements on the part of tools be combined into a strategy to provide computational support for design decisions on the selection of energy saving building components?
- Can a prototype be developed that demonstrates how the proposed changes actually lead to better integration of design and simulation, and hence to improved computational support for design decisions with respect to the selection of energy saving building components?

In order to answer the research questions the following research steps have been taken: the development of a strategy to provide computational support during the building design process for the selection of energy saving building components (de Wilde and van der Voorden, 2003b) and development of a substantiating prototype that shows how the strategy can be implemented in a novel support systems (Augenbroe and de Wilde, 2003).
The strategy development, which is described in paragraph 6.1., consists of:

- analysis of the key elements needed to provide computational support for the selection of energy saving building components, assessment of whether the ideas presented in chapter four and five provide these elements, and the filling of remaining gaps (paragraph 6.1.1.);
- actual development of the strategy to provide computational support for the selection of energy saving building components (paragraph 6.1.2.).

The prototype development, which is described in paragraph 6.2, consists of:

- definition of an approach for this prototype development (paragraph 6.2.1.);
- actual development of the prototype (paragraph 6.2.2.);
- assessment of the viability of the resulting prototype (paragraph 6.2.3.).

Paragraph 6.3 concludes the chapter by summarizing the results of this chapter, positioning the strategy in the context of building design in general and the prototype in the context of the strategy, and by presenting overall conclusions and remarks.

Both research steps of strategy and prototype development have been supported by participation of the author in an international research project: the Design Analysis Integration (DAI)-Initiative (Augenbroe and de Wilde, 2003; Georgia Institute of Technology, 2003). The objective of the DAI-Initiative is to enable a more effective and efficient use of existing and emerging analysis tools by building design and engineering teams, taking a process-centric approach. Its main goal is establish a proof of concept prototype of a support environment that demonstrates how process scenarios can provide a logical point of entry to building design analysis by connecting building design and building performance assessment tools. For the work presented in this chapter, the DAI-Initiative provides two essential contributions: a sound theoretical basis for the link between performance assessment needs and building performance analysis tools, and prototype development. In paragraph 6.1 theory from the DAI-project will be introduced to complete the strategy. Paragraph 6.2 will deal with prototype development and present the DAI-Initiative in more detail, including a description of the fit between the PhD-project and this specific research initiative. Appendix E presents additional information on this project.

6.1. Strategy Development

The strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components is to meet the following requirements that have been identified throughout this thesis:

1. overcome the barriers for integration of building design process and building simulation that have been identified in earlier efforts: unavailability of appropriate computational tools or models, lack of trust in computational results, the high level of expertise needed to fully utilize building simulation tools, the issue of costs (time and money), and the problems related to data exchange between 'design' and 'simulation' (chapter two);
2. address both the building design process and computational tools at the same time, instead of focusing on either process or tools (chapter three);
3. provide one common process/procedure for selection of energy saving building components, synchronizing the activities from different participants in the process, but allowing for iteration between the steps and not enforcing a rigid sequential process (chapter four);
4. ensure that analysis tools meet the following requirements:
    - o be able to accommodate specific building design options, provide the information as requested for the upcoming selection, allow rapid analysis of the relevant performance aspect, and be applicable during early design phases;
    - o be accompanied by accurate information on the building design alternatives and performance indicators that any specific tool can handle (chapter five);

5. ensure that support environments meet the following requirements:
   - provide access to a suitable tool for relevant steps of the selection procedure, manage information exchange between user and embedded tools, and provide additional functions to the user when compared to the function(s) of the embedded tool(s);
   - contain a set of different analysis tools in one performance domain (e.g. energy analysis), allowing to use the best tool for one specific analysis task, and provide a mechanism that determines which tool is most suitable to perform a specific task (chapter five);
6. if possible, break the trend towards increasing capabilities and complexity of new building performance assessment tools.

6.1.1. Analysis of Key Elements

The previous chapters provide the following key elements that can be used to develop the strategy:

- In chapter four a performance-based approach for the selection of energy saving building components has been developed. This approach improves decision-making on the selection of these components from heuristic search (as is current practice, see chapter three) to partial search that allows to find the best option from a given set of design alternatives. The approach consists of the following main steps:
  - definition of an option space;
  - identification of relevant functions;
  - specification of performance indicators (plus objectives, requirements and constraints);
  - prediction of performance for all options and all performance indicators;
  - evaluation of predicted performance, and selection of the most desirable option.
- Chapter five assessed support provided by existing tools for selection of energy saving building components according to the performance-based approach. It was found that analysis tools and support environments are the most important tools to support this selection. Existing analysis tools are capable of supporting the selection according to the performance-based approach, on condition that enough time and expertise is available for the modeling and simulation work. Reverse-engineering of these tools will help users to access the tools functions needed for specific tasks. Support environments can also play an important role, especially if they provide a mechanism to select the best tool for a given task.

While these elements ensure that the strategy will address both the building design process and computational tools, and while they provide a common procedure for selection of energy saving building components, they do not yet provide a solution for accessing suitable, reverse-engineered building analysis tools. This missing link has been developed in the DAI-Initiative (Augenbroe and de Wilde, 2003; Georgia Institute of Technology, 2003; Augenbroe *et al*., 2003):

- The DAI-Initiative has introduced the concept of analysis functions to define a clear relationship between analysis processes and the actual use of analysis tools. Analysis functions are based on the assumption that design processes generate a number of typical analysis request that are common across most building projects, and that a set capturing most of these typical analysis request can be identified. For each recurring typical analysis request the expert consultant will then apply a similar analysis process: a typical analysis scenario. Within these analysis scenarios a set of recurring specific tasks will deal with the actual analysis work. These recurring atomic tasks are the analysis functions that provide a standardized set of entry points for the application of analysis tools in an analysis scenario. The set of analysis functions can be linked to a set of corresponding tool functions (named analysis tool functions) that allow to actually perform those analysis functions. Analysis functions provide:

- a clear point of entry to available analysis tool functionalities (of one, or of multiple tools that qualify for a specific analysis task);
- a communication language that allows to define exactly what analysis work is needed, in the form of: 'predict the performance of building (sub)system A for performance aspect B under conditions C, according to measurement protocol D and assuming the aggregation E of observed states';
- a scoping mechanism that allows to ship only the essential information to a tool (data-pull instead of data-push).

Analysis functions are a selection mechanism for suitable tools. They are a typical concept to be included in a support environment, linking process management tools with analysis tools. Analysis functions are defined in a analysis tool-independent manner, allowing for easy adaptation once future analysis tools become available.

6.1.2. A Strategy for the Selection of Energy Saving Building Components

The ideas of chapter 4 and 5 and the concept of analysis functions from the DAI-Initiative can now be combined into the following *strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components*:

1. Energy saving building components should be selected according to a procedure that consists of the following main steps:
    - definition of an option space, that includes a zero-option (building design without energy saving building components as reference situation) and different design alternatives that include one or more energy saving building components;
    - identification of relevant functions, including 'make building energy-efficient', 'maintain thermal comfort' and others as applicable;
    - specification of performance indicators (plus objectives, requirements and constraints);
    - prediction of performance for all options and all performance indicators (energy efficiency, thermal comfort, etc);
    - evaluation of predicted performance, and selection of the most desirable option, preferably using an additive utility function.
2. Availability of time and expertise for modeling and simulation work are the most important limiting factors that hinder the application of existing building performance assessment tools in a building design context, like the selection of energy saving building components. In order to overcome this problem:
    - the analysis request must be stated unambiguously, defining what analysis function is required from a building design decision-making point of view in terms of:
        - building (sub)system(s), describing the building and energy saving building components that are to be assessed;

        - relevant performance aspects like energy efficiency, thermal comfort, etc;
        - testing conditions like climate regime, occupant behavior, HVAC-settings etc;
        - measurement protocol, specifying which states must be observed at which points in time;
        - aggregation of observed states into performance indicators.
    - building performance analysis tools must be pre-conditioned (reverse-engineered) in order to meet these specific analysis requests. Once an analysis tool qualifies for an analysis function, it is perfectly clear what building design alternatives and performance indicators that specific tool can handle.
3. In order to enable the use of analysis functions as a selection mechanism for qualifying analysis tools, the selection of energy saving building components should be assisted by the use of a support environment that contains the analysis functions as well as a set of qualifying analysis tools. This support environment should also provide a standardized user interface, allow interaction between various tools, contain building product models, common databases, and other instruments like process modeling tools, information modeling tools, decision-making methods, etc. that help to support the different activities that make up the procedure described above in an actual building design context.

This strategy meets the requirements in the following way:

- Barriers for integration identified in earlier efforts:
    - The strategy provides better access to appropriate analysis tools and models, by specifically defining the analysis request and matching those to available analysis tool functionalities.
    - In doing so, the strategy limits data exchange between building design process and analysis tool to the essential information, thereby minimizing problems related to data exchange.
    - The strategy supports modeling efforts by specifying the aspects that need to be considered when modeling an analysis request. However, there is still a need for expertise while selecting an appropriate analysis function.
    - The strategy provides no specific elements that address costs (time and money) of analysis efforts. However, the use of analysis functions allows maximal automation of analysis work, thereby reducing simulation efforts (especially in the field of modeling).
    - At the current state no claims can be made regarding an increase in the trust in computational results. However, it is clear that a better communication about analysis request and tool capabilities will improve the communication between ‘design’ and ‘analysis’, in the long term resulting in improvements in this field.

- Process and tools:
  The strategy addresses the building design process and computational tools at the same time, instead of focusing on either process or tools. The strategy provides one common procedure for selection of energy saving building components, implementing the approach that has been developed in chapter four.

- Integrating analysis tools in a support environment:
  Because of its general nature, the strategy addresses the requirements for applicability of tools in a design context in general terms only, requiring tools to be pre-conditioned (reverse engineered) to meet specific design analysis requests. Paragraph 6.2. will discuss the development of a prototype that substantiates this idea.

- Breaking the trend towards increasing tool capabilities and complexity
  In this respect the strategy faces a trade-off. On the one hand, it aims for a transparent structure and easy of use of analysis tools. On the other hand, it has become obvious that analysis tools and support systems must deal with real-life complexity, and that it is unwise to try to capture this in over-simplified structures that fail to deal with the real-life problems that are to be addressed. The strategy takes the approach of reducing these problems by unraveling the full complexity through separation of process and tools, and by subsequently building bridges between these two by the means of analysis functions. It is hoped that this modular structure will better meet design analysis needs than current one-seize-fits-all approaches.

Note that while the strategy ensures that critical steps that are needed for a well-founded selection of energy saving building components are taken, it does not prescribe a specific approach to building design. Thereby the strategy can be applied by different actors who tackle building design according to their personal preferences. Also note that the strategy can be applied by different actors, like architects, consultants, clients etc.

6.2. Prototype Development

In order to demonstrate the feasibility of the strategy, a prototype has been developed that demonstrates how actual improved computational support for design decisions with respect to the selection of energy saving building components can be achieved. This prototype development coincides with the prototype development of the DAI-Initiative. Participation in this project was a logical follow-up to the work presented in the previous chapters, allowing a much more rigorous and universal research and development effort than would have been possible through a one-man project.

The development of a prototype that shows the feasibility of the strategy as developed in paragraph 6.1 needs to:

1. harness the approach (scenario) for selection of energy saving building components;
2. provide an unambiguous point of entry to analysis tools, allowing to define what analysis is required and giving access to qualifying tools;
3. have the form of a support environment that supports the use of embedded analysis tools in a design context.

Most current research and development efforts in the field of integration of building simulation and building design focus on data exchange; only very few take a process centric approach[36]. Of the work that does consider a process dimension the most prominent is the Building Lifecycle Interoperable Software project BLIS (2003). However, that effort is not able to harness an approach for selection of energy saving building components as developed in chapter four, since it provides handles to use of software (named 'views') on a more

[36] See for instance section 2.3.3. that describes state-of-the-art efforts in integration

general level only. Other work that acknowledges the importance of the process dimension is the research carried out at the Energy Systems Research Unit at the University of Strathclyde (e.g. Hand, 1998), expanding on earlier work on process modeling using Petri-net techniques from the Combine project (Augenbroe, 1995). However, this work mostly focuses on managing simulation efforts with the simulation engine ESP-r. The DAI-Initiative alone provided an opportunity to work on a prototype support environment that was capable of capturing and supporting highly flexible processes (scenarios), access a suite of relevant analysis tools, and link process and tools in a well-defined manner.

The fit between the work described in this thesis and the DAI-Initiative is not coincidental, since this project was initiated by established research partners[37] with similar research interests, who where involved in the ongoing PhD-research (see e.g. de Wilde *et al.,* 1998), albeit with a stronger emphasis on building product model technology (Augenbroe and Eastman, 1998). The author of this thesis was involved in all activities of the DAI-Initiative project[38], including development of underlying theories, software development and application, and reporting. Through this involvement the DAI-Initiative became strongly focused on design analysis efforts that are needed in the context of making design decisions on selection of one design alternative from a set of options, thereby increasing the applicability of the DAI-prototype to support for the selection of energy saving building components and maximizing synergy between the work presented in this thesis and the DAI-Initiative.

In advance on the subsequent discussion of the DAI-Initiative[39] the following contributions of the author of this thesis can be stated:

- all work on the process modeling (scenarios) and most work on enactment of these processes/scenarios;
- most work on the definition and development of the three analysis functions included in the prototype, starting with the choice for these specific analysis functions and developing them from a description in words to descriptions in Express-G, Express and XML;
- all work on hand-implementing information in the XML documents to stub-implement the information layer of the workbench;
- overview of the development of the interfaces between XML documents and the simulation tools EnergyPlus and Idea-L that was carried out by others;
- development of the dummy pop-up screens that are called from the scenario layer.

6.2.1. The Design Analysis Integration (DAI)-Initiative

The goal of the DAI-Initiative is to develop credible solutions to the integration of building performance analysis tools and the building design process. These solutions are to enable a more effective and efficient use of existing and emerging building performance analysis tools by building design and building engineering teams. Spearheads of the project are an improved functional embedding of performance analysis tools in the design process, increased quality control for building analysis efforts, and exploitation of the opportunities provided by the Internet (in particular the possibilities for collaboration of loosely coupled teams, allowing the execution of specific building performance analysis tasks by (remote) domain experts).

[37] Professor Augenbroe, who also supervised part of the work on this thesis.
[38] The author of this thesis was full-time researcher working on the DAI-Initiative, taking a central role in the project and contributing to all tasks.
[39] See the remainder of this paragraph for an in-depth explanation of the items named in this list of contributions.

In order to reach this goal the DAI-Initiative aims to provide a layered approach to support the interaction between the building design process and building performance analysis tools. This approach is to be substantiated by a proof of concept prototype of a support environment that connects building design process and analysis tools. The prototype support environment is realized in the form of a workbench that distinguishes different layers that are important when carrying out analysis tasks. These layers enable the user of the workbench to concentrate on specific layers that are relevant for specific stages of his work, while maintaining the overall consistency of the analysis. The workbench positions building design information and tools on opposite layers; the intermediate layers function as a scoping mechanism or filter to transfer relevant information only to the tool layer. The intermediate layers provide context to any interaction by capturing the relevant process and modeling aspects, each on a separate layer. See figure 6.1.

The top layer contains all building design information in partly structured and partly un-structured format. The building model layer contains semantic product models of varying granularity that can be used for specific analysis domains or performance aspects. The scenario layer captures the process logic, allowing both to plan a process as well as to actually go through that process. Finally, the tool layer contains software applications (analysis tools) that can be accessed from the scenario layer to perform a specific analysis. The concept of analysis functions, which has been described in paragraph 6.1.1. of this thesis provides the mechanism that links the scenario with analysis tools, while calling relevant models and information from the upper layers.

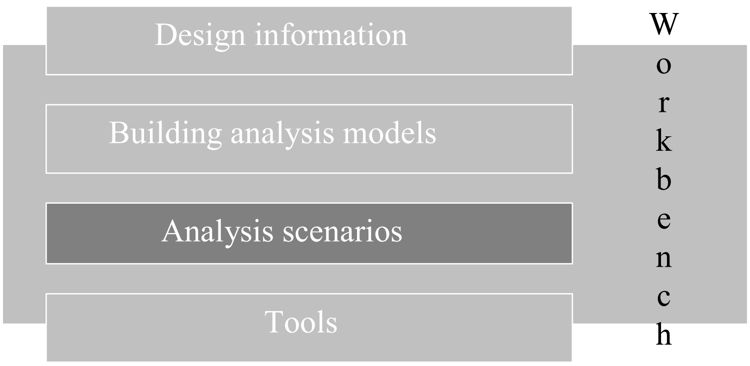


Figure 6.1: Workbench-approach of the DAI-Initiative

The following assumptions are fundamental to the development of the workbench:

- The workbench is to be process-centric, and must allow for explicit definition, management and execution of analysis scenarios. This provides additional useful functions, as this allows to store audit trails of any building analysis, reuse of previous scenarios in new projects and provides a support instrument for novices to building performance analysis. As analysis scenarios can be repeated it is easy to support incremental design analysis cycles.
- Expert knowledge and expertise are essential elements of careful building performance analysis. Judgment of the applicability of performance analysis methods and evaluation of the validity of results obtained with (analysis) tools are hard to capture in support

environments[40]. The view that experts need to remain actors in the design process is in line with the observation that building design is becoming more and more team work, with specialists collaborating and contributing to the design. Therefore the workbench assumes an expert consultant as user, who is contributing to a design team effort.

The following limitations have been applied to the prototype development, in order to guarantee the feasibility of the project:

1. In the first stage of the project the focus of the DAI-Initiative is on thermal building analysis. However, to show the applicability of the approach to other fields an example in the field of daylighting is included as well. Yet in principle the approach can be applied to all performance domains (acoustics, structural engineering, etc).
2. A first set of only three analysis functions, linked to corresponding building aspect models and analysis tool functions is included in the prototype. The link between model layer and information layer will not be addressed at this stage, but will be stub-implemented only.

The prototype workbench as developed in the DAI-Initiative provides all elements needed to meet the requirements for showing the feasibility of the strategy: the scenario layer captures and supports the selection procedure, the analysis functions link the scenario to qualifying analysis tools, and the overall workbench combines all elements into a support environment.

6.2.2. Approach

The development of the prototype took place in a modular, incremental way, that consisted of the following three main phases:

1. *Requirement specification*

   In order to get an overview of requirements for the DAI-Prototype a mock-up was made that demonstrated the major functions of the intended prototype. The mock-up shows how the workbench-approach provides process support, gives access to analysis tools, helps to configure building analysis models, and provides additional functions like audit trails and explicit quality assurance procedures, all in the context of everyday building analysis work. It was used for discussion of the underlying ideas and approach underlying the prototype development with the tool user community (expert tool users and consultants) through a number of workshops.

   As the DAI-Prototype needs to be process-centric, repetitive activities in the day-to-day practice of energy analysis work that can benefit from process support (typical analysis scenarios) were identified. A representation method was selected to represent analysis scenarios. Three analysis functions were selected for further development.

   Based on the experiences with the mock-up, the feedback from the workshops and the findings regarding analysis scenarios the requirements for the DAI-Prototype were analyzed and written down as a formal specification of requirements. These requirements are described in detail in appendix E of this thesis.

2. *Actual building of the prototype*

   The next step was the actual development of the DAI-Prototype. The prototype was built on an existing commercial platform for process management, adding components to

[40] Tools that are to be used without knowledge of the applicability of the underlying models or that do no not allow evaluation of the validity of the results become black boxes to their users, thereby reducing trust in their results.

interface with the other layers. Note that only some of these components allow for actual live connections; others are mock-up connections.
In order to demonstrate the concept of selecting relevant analysis functions, and of providing access to the tool layer from these analysis functions, the DAI-Prototype contains the building energy simulation tool EnergyPlus, as well as the lighting simulation tool IDEA-L. A set of pre-defined analysis functions linked to these tools is available during process definition. During process enactment all necessary steps to perform the analysis can be demonstrated.

3. *Demonstration and assessment*
   The resulting DAI-prototype has been tested during a final workshop with the user community. This provided feedback on the viability of the workbench in real practice, and helped to define follow-up efforts for further development of the prototype.

6.2.3. System Development

The DAI-Prototype was developed in an incremental, modular way, starting with a first mock-up version. This mock-up was discussed with tool users in a total of three workshops. Overall these workshops confirmed the relevance of the process dimension in building energy analysis. Consultants recognized the occurrence of recurring questions posed by designers (typical analysis requests) and agreed that their day-to-day practice involves a number of repetitive activities and processes (typical analysis scenarios) that could benefit from process support. Throughout the further development of the DAI-Prototype close contact with tool-users was maintained by means of small, one-to-one meetings which allowed step-by-step testing of assumptions. Two of those smaller meetings have been realized.

The following components that make up the ingredients of DAI-Prototype prototype have been developed: a storybook, workflow design and enactment, analysis functions, and interfaces to tools.

Storybook
The development of the DAI-Prototype started with the creation of a storybook that describes a simple analysis process: the analysis work needed to support selection of a glazing system during the design of an office cell. The storybook provides the a number of typical elements that are encountered in the process context for building analysis efforts: the initial design analysis request from a designer/architect, the planning of the analysis efforts, the actual execution of the analysis, modification of the analysis plan during the actual analysis work, and the final feedback provided to the designer/architect. The storybook explains how the technology of workflow management systems (WFM) can be used to plan an analysis process by defining an analysis scenario (workflow design), and subsequently to execute those scenarios (workflow enactment). The storybook also shows how audit trails, monitoring and reuse of previous analysis scenarios fit in the overall picture. Underlying technology is Microsoft PowerPoint. Some elements of the storybook are depicted in figure 6.2.
The storybook provided the background for development of a simple mock-up of the DAI-Prototype, made as a webpage in HTML. Basically this mock-up represented the four layers of the workbench, while hyperlinks showed access to (non-operational) applications on those layers. Neither the storybook nor the mock-up contained live components; all process models and other elements were simple screen-dumps.

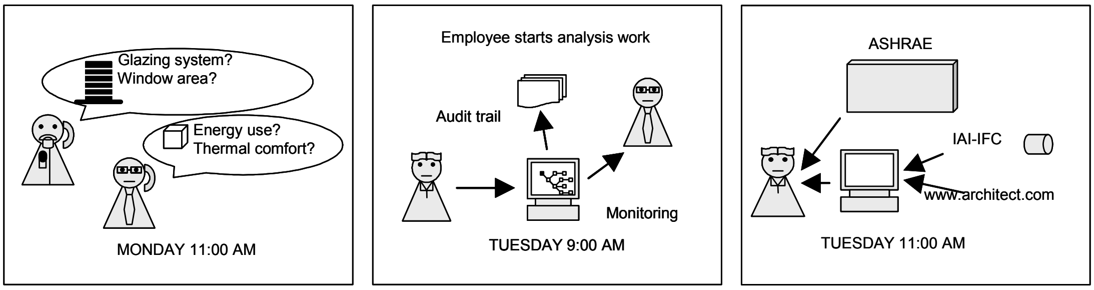


Figure 6.2: Part of the storybook

Workflow Design and Workflow Enactment
The workflow design and workflow enactment deals with the planning and executing of analysis scenarios. The efforts in this field started with the development of one analysis scenario for the selection of a glazing system for the simple office cell. This analysis scenario adhered to the principles of performance-based design decision-making as developed in chapter four, resulting in a process that consists of the familiar steps of development of an option space, identification of relevant functions, specification of performance indicators, prediction of performance of design options, and evaluation of predicted performances.

Efforts on process modeling started using the Workflow BPR process modeling method. This software was selected because it allows graphical representation of processes as detailed process flow diagrams that can be constructed using drag-and-drop capabilities. It is easy to understand and to apply, which makes it suitable for use by persons who do not have a specific background in process modeling or workflow management. It also allows to decompose processes, describing the tasks that make up a (sub) process in a separate window. In later phases of the project Workflow BPR has been replaced with a newer version of the same software named BPM Workbench (Holosofx, 2002). BPM Workbench allows to export processes to a workflow enactment engine: a computer program that automates the transfer of documents, information or tasks between the actors and tools used in an organization. One workflow engine that can be used with BPM Workbench is IBM MQ Workflow (IBM, 2002). Other process modeling methods and workflow management systems have been assessed as well. However, the combination of BPM Workbench and IBM MQ Workflow was the one and only option that allowed to meet the requirements for the process modeling method and combine this with robust workflow enactment.

BPM Workbench uses the following items to model processes:

- Tasks: the activities that make up the process; tasks cannot be decomposed. Tasks are represented as octagons.
- Processes: the activities that have been decomposed; processes contain tasks and other process objects. They are represented by rectangles.
- External entities/processes: actors outside the control of the organization that carry out the process, and the processes carried out by those external entities. Both are represented as oval.
- Phi's: the representation item for the input and output of activities; the name and symbol reflects an I for input and an O for output overlapped, forming the Greek character phi.

- Decisions and choices: decisions influence the routing of the process; each choice then points to the flow path belonging to that choice. Decisions are represented by diamonds, choices by small circles.
- Connectors: the arrows that connect the other items in order to make flow diagrams.
- Go-to objects: elements that allow to construct shortcuts to a connection far away in the diagram, as well as to construct loops (named rework in BPM Workbench); represented by small stars or triangles.
- Stops: items that show that a certain path has come to an end; represented by an octagonal stop sign.

An example of a process model constructed in BPM Workbench is shown in figure 6.3.

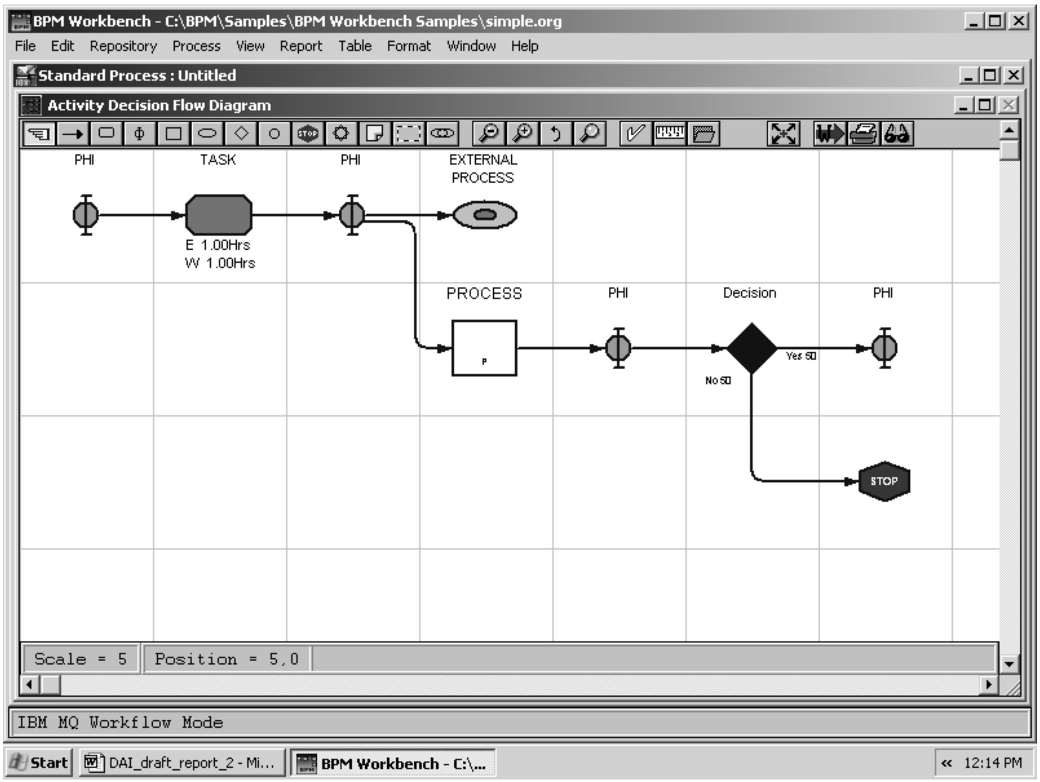


Figure 6.3: Simple process model in BPM Workbench

BPM Workbench allows to design processes, but is not suitable to enact those processes. As mentioned above, processes made in BPM Workbench can be exported to workflow management engines. In this case the IBM MQ Workflow (IBM, 2002) engine has been used, as this is a robust, task-based system (MQ = message queue). Items defined in BPM Workbench are translated into corresponding items in IBM MQ Workflow, for instance tasks become activities, the phi's become data flow, and the connectors are translated into a control flow.

Analysis Functions

Analysis functions are the key to the connection of the scenario layer with the building model and tool layers. They allow the consultant / domain expert to specify exactly what needs to be analyzed, without any constraint on how that analysis is to be carried out. They describe the analysis from a design driven perspective. Analysis functions must include a functional description of the building (in the sense of system) under consideration; they also must define an experiment needed to generate states that can be observed and analyzed to derive the performance of that building (system) for a given performance aspect. Thereby analysis functions are in fact an instrument to unambiguously define performance indicators. Yet this does not say anything about how the performance indicator value is obtained – this might result from building performance simulation, but expert assessment or an experimental set-up could be used as well. See figure 6.4.

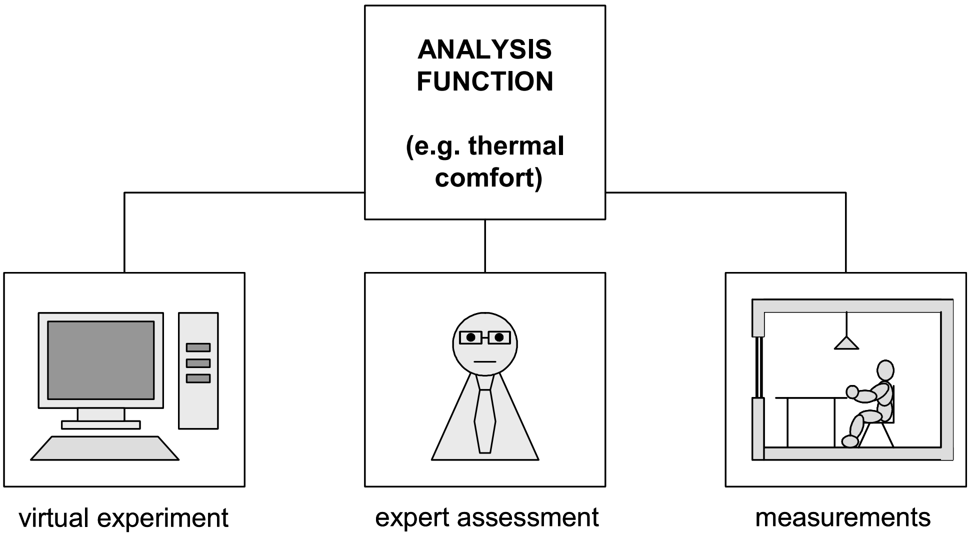


Figure 6.4: Different options for obtaining performance indicator values for a specific analysis function

For the development of the DAI-Prototype, three analysis functions were developed, starting from the test case addressing the selection of a glazing system for the office cell and the corresponding analysis scenarios. For that specific case, the option space was limited to three different glazing types (single glazing, double glazing and low-e glazing). Relevant functions performed by the glazing system were identified as 'maintain thermal comfort' and 'make office cell energy-efficient', which can be measured through PMV values as defined by Fanger (1970), and heating and cooling loads. Another non-thermal performance aspect that is important for the selection of glazing systems is daylighting access. This can be measured by calculation of the daylighting autonomy (percentage of office hours that the office does not need artificial lighting).

The development of the three analysis functions took place in a number of steps. First of all, a description of the analysis function was created using human language, set down in an informal standard in a Microsoft Word document. Using these documents the performance analysis as described was carried out, using actual energy and daylighting simulations. Based on the findings missing information was added to the documents, whereas deficiencies in the descriptions could be identified.

As a description in words cannot be read directly by a computer (because of the fact that the translation of this description to input for building performance analysis tools always involves expert interpretation), the next step was to develop a unambiguous, machine-readable version of the three analysis functions. In order to do this formal diagrams depicting the relevant entities, attributes and relationships captured in the descriptions of the analysis functions were developed. These formal diagrams were then translated into schemes in computer code. This code was then used to develop an actual instance of each schema, matching the original description in words and removing any remaining deficiencies in those earlier descriptions.

In order to carry out the above-mentioned developments existing STEP (STandard for the Exchange of Product model data) technology has been used (Eastman 1999, chapter 5). Basically, STEP is a standard for data exchange that has been developed since the mid-eighties to provide a complete, unambiguous, computer-interpretable definition of the physical and functional characteristics of any product throughout its life cycle. This is realized by the use of the computer language EXPRESS that allows to specify the structure of data and the relationships between data-items. A structure as specified in EXPRESS can then be used to store actual data on a product, for instance data describing a specific building. Step technology is already in use in the building industry; examples are the integrated data model IDM as developed in the COMBINE-project (Augenbroe, 1995) and the ongoing IAI-IFC project (International Alliance for Interoperability, 2002). The EXPRESS language also has a graphical version, which is named EXPRESS-G. EXPRESS-G allows to make a graphical representation of an EXPRESS schema. For the development of machine-interpretable analysis functions the original descriptions in words were used to define diagrams in EXPRESS-G. Those diagrams were then translated into EXPRESS schemas and populated. As the DAI-Prototype aims to work in an internet-based environment, data transport using XML technology was the preferred option. Therefore an additional step was made: the EXPRESS schemas were translated into XML schemas, whereas the population of those schemas now was made using XML documents.

A description of all elements of an analysis function is given in appendix F, that contains the full version the definition in words in the informal standard, EXPRESS-G diagram and EXPRESS code for the analysis function that deals with energy efficiency of the office cell. The XML schema and exemplary XML document are too large for inclusion in this thesis or appendix; however, they can be viewed on the DAI-website (Georgia Institute of Technology, 2003). Here only a short discussion of the main elements of the analysis functions is given in order to convey the underlying ideas:

Overall, an analysis function defines an experiment needed to generate states that can be observed. From these observed states the functional performance of the building (or building sub-system, like for instance a room) for a specific performance aspect can be derived. Each experiment is defined by the following main elements:

- The experimental set-up being observed (the “test box”)
- The experimental conditions to which the set-up is exposed (the “load” that is applied to the test box)
- The observation schedule that is used for observation of the generated states (the “measurement protocol” or “timetable”)
- The observed states are intrinsic to each analysis function (experiment), and hence are not specified in the description. However, depending on the analysis function in question there is an option to specify how the observed states are to be aggregated into the Performance Indicator.
- Each analysis functions also has:

- An analysis function name, which allows to check that an analysis function description is sent to a building performance tool that qualifies for that specific analysis function;
- A process ID, which allows to match the analysis function instantiation to a specific analysis scenario;
- A timestamp, which allows to discern between multiple calls to one and the same analysis function that might occur during one process.

For each individual analysis function, the entities and attributes that are described by the experiment are based on a design analysis view. For instance, the analysis function for the assessment of thermal comfort is based on the decision to evaluate thermal comfort using PMV-values as defined by Fanger (1970). Because of this, the analysis function needs to describe those entities that are needed to calculate PMV-values: there needs to be an internal air zone that has an average air temperature, and there need to be surfaces that have temperatures that can be used to calculate a mean radiant temperature. Also, occupants need to be defined that have a metabolic rate and clothing value. However, if the decision had been made to base the thermal comfort analysis function on a different analysis principle, for instance the use of degree hours for the air temperature, then there would not have been a need to include any occupant and occupant properties, and the treatment of surfaces might have been different. Note that different analysis functions for thermal comfort, like a PMV-based and a degree hour-based function, can co-exist in the DAI-Prototype. See figure 6.5.

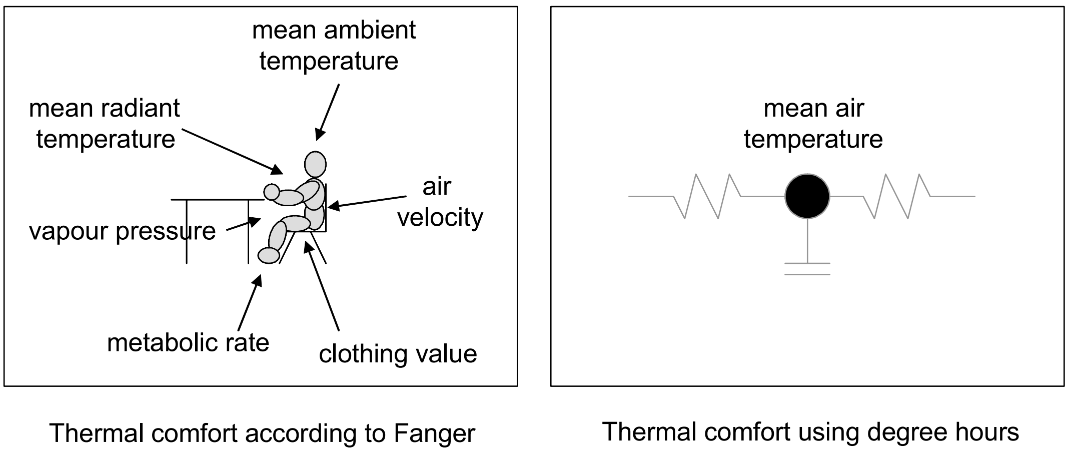


Figure 6.5: Different analysis functions for quantification of thermal comfort

Interfaces to Tools

In order to do the analysis as identified for the three analysis functions (energy efficiency, thermal comfort and daylight autonomy), existing analysis tools have been embedded in the tool layer of the prototype. For the thermal building aspects the dynamic building simulation tool EnergyPlus (US Department of Energy, 2002b) has been selected. EnergyPlus is a relatively new simulation tool, using a modular structure. Moreover, EnergyPlus is only a simulation engine; it does not come with extensive user interfaces or shells, because the development team of EnergyPlus anticipates that those will be developed by commercial parties. This allows the DAI-Prototype to interact directly with the engine and lead the way to a novel type of user interface, replacing current static interface approaches. However, in principle any existing thermal simulation tool might qualify for carrying out the analysis as specified by the analysis functions. In the end it is envisioned that the tool layer will contain a set of relevant tools, that can be called for matching functions.

For the computational analysis of daylight autonomy use has been made of the lighting tool IDEA-L (Geebelen and Neuckermans, 2001; Geebelen, 2003). IDEA-L is under development as a tool intended for use in early phases of the building design process. Its main objective is not to produce impressive images for presentation purposes, but to allow design teams to make fast and reliable assessment of daylighting performance. Just like EnergyPlus, IDEA-L is basically a computational engine, allowing optimal embedding in the DAI-Prototype. Again, other lighting tools can be embedded on the tool layer as well, like the mainstream lighting simulation program Radiance.

For both EnergyPlus and IDEA-L the information contained in the analysis functions needs to be parsed to an input file for the simulation tool. Also, specific information needs to be added to allow the simulation to start (providing tool settings, locations of relevant libraries etc to the tool). Therefore, specific interfaces have been developed that transfer the data from the XML document to the simulation tools. As the XML files always adhere to the XML schema that describes the structure of the XML document, such an interface needs to be made only once for each combination of analysis function and tool. Therefore three interfaces have been made: one from the analysis function ‘thermal comfort’ to EnergyPlus, one from the analysis function ‘energy efficiency’ to EnergyPlus, and one from the analysis function ‘daylight autonomy’ to IDEA-L. It is important to note that these interfaces are relatively easy to develop, as they parse information from a dedicated, minimalistic product model, instead of a complex neutral model that contains a lot of redundant information. Therefore development and validation of these interfaces is easier then development of full interfaces to neutral models.

Prototype
All of the above elements have been brought together in one DAI-Prototype. On the scenario layer this prototype contains the workflow design tool BPM Workbench and the workflow enactment engine IBM MQ Workflow. On the model layer it contains the analysis function structures described in XML schemas. The information layer is stub-implemented by actual instances of analysis functions described in XML documents. The tool layer contains the embedded simulation tools EnergyPlus and IDEA-L, which are linked to the analysis function models by the specific interfaces. The DAI-Prototype is embedded in a Microsoft PowerPoint presentation that contains many elements of the storybook. This allows to use the prototype for demonstration sessions with an audience that needs to be introduced to the underlying ideas and principles: the presentation gives a simple process context, and also helps to explain how the different elements of the prototype interact.

The DAI-Prototype currently provides the following functionalities:

- An analysis scenario can be defined in the prototype, and existing processes can be reused. For demonstration purposes the elements of existing scenarios can be rearranged and reconnected to make new processes, without having to redefine all tasks and links between those tasks and applications embedded in the prototype.
- The scenario that has been defined with appropriate elements can then be enacted. This will result in all tasks coming up in the appropriate sequence (as defined), whereas the prototype will provide access to applications that are relevant for each of those tasks.
- The principal tasks that relate to the layers of the workbench that have been targeted during the first stage of the DAI-Initiative have mostly been fully enabled: there is access to analysis function structures, analysis function population, control over the operation of the interfaces to the simulation tools, and an option to view results. Tasks that do not

relate to the core issues are not operational; here stub-implemented applications (simple executables that only produce a pop-up screen, developed using C++ Builder) are used to provide a feel of the support that can be expected from future versions of the DAI-Prototype.

- Apart from the actual enactment, the workflow engine allows to monitor progress of the analysis process, and keeps an audit trail that can be inspected.

6.2.4. Viability

It is now possible to demonstrate how the DAI-Prototype shows the viability of the strategy to provide computational for rational design decisions regarding the selection of energy saving building components in a design context. This demonstration will describe how the DAI-Prototype meets the criteria for showing the viability of the strategy as stated in paragraph 6.2:

1. harness the approach (scenario) for selection of energy saving building components;
2. provide an unambiguous point of entry to analysis tools, allowing to define what analysis is required and giving access to qualifying tools;
3. have the form of a support environment that supports the use of embedded analysis tools in a design context.

Some remarks on the viability of the support environment as realized with the DAI-Prototype will be added to this paragraph.

Support for the procedure for selection of energy saving building components:
In chapter four a procedure for the selection of energy saving building components has been described that consists of five main steps: development of an option space, identification of relevant functions, specification of performance indicators, objectives, requirements and constraints, prediction of performance of the design options, and evaluation of predicted performance and selection of the most desirable option. In the DAI-Prototype these steps can be described in an typical analysis scenario through the development of a corresponding workflow model in BPM Workbench. See figure 6.6.

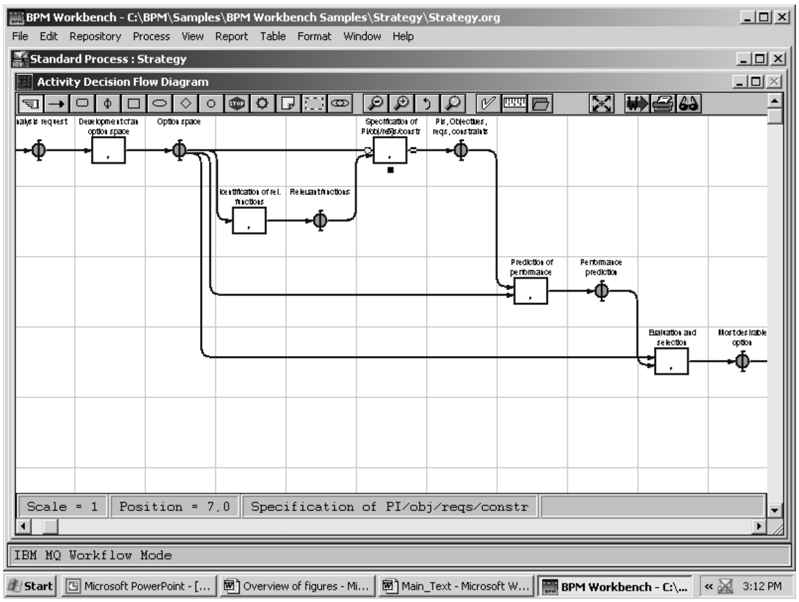


Figure 6.6: Process model of the procedure for selection of energy saving building components in BPM Workbench (top level)

The diagrams showing decomposition of the top level process are depicted in figure 6.7 a, b, c, d and e. The underlying ideas of these diagrams is discussed in detail in chapter four. Note that in order to simplify the models and increase their readability no feedback-loops (reworks) have been included here. However, in real practice such loops enhance the usability of the model in practice. Rework options allow the user of the model to redo the previous task or tasks before moving on to the next task, like modifying the options space after a first prediction of performance has been done, predicting the performance of the new options, and only then moving on to the task of evaluation and selection.

Note that it is easy to modify this scenario, for instance to match new insights on procedures for the selection of energy saving components or to meet the ideas of one specific consultant wanting to do some tasks in a different way or sequence. This allows for evolution of the procedure in order to meet new demands and insights, and allows the set-up to flexibly match future developments.

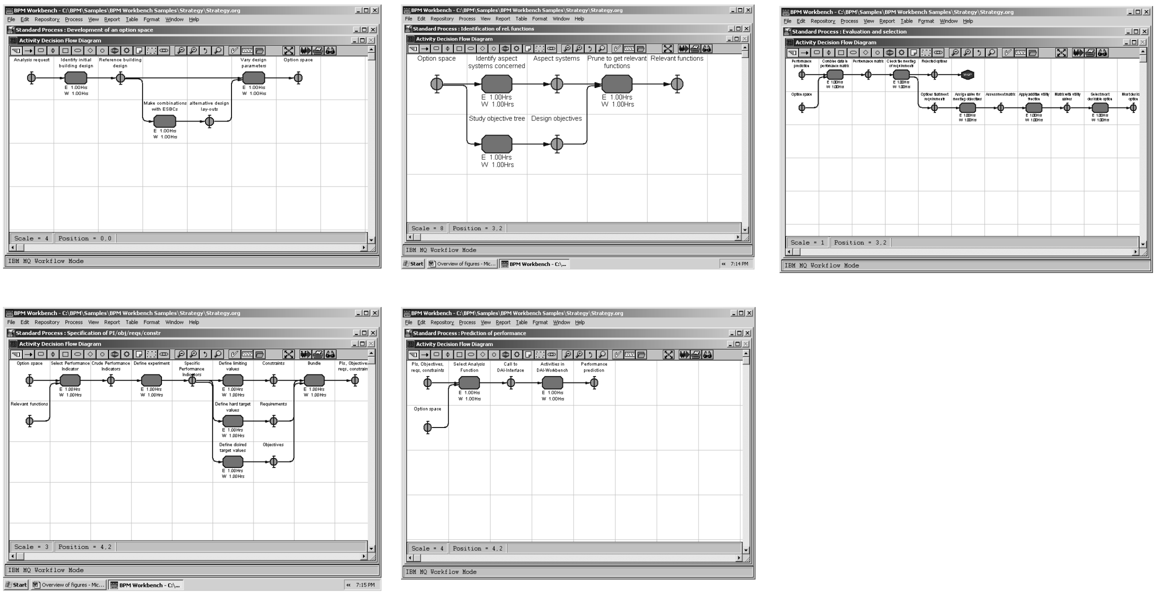


Figure 6.7: Process model of the procedure for selection of energy saving building components in BPM Workbench (decompositions)

The next step of using the DAI-Prototype would be to enact this process model (scenario) in the IBM MQ Workflow engine. This will result in tasks showing up on the desktop, according to the sequence and interdependencies as defined in the process model. To convey the flavor of enactment figure 6.8 shows a first message from the workflow engine and the navigation screen provided by the message. This message informs a user of the DAI-Prototype that the workflow engine has assigned a task. Navigation buttons allow to review a description of the task, call an email-program to communicate with others about this task, and of course allow to confirm acceptance of the task to the workflow engine.

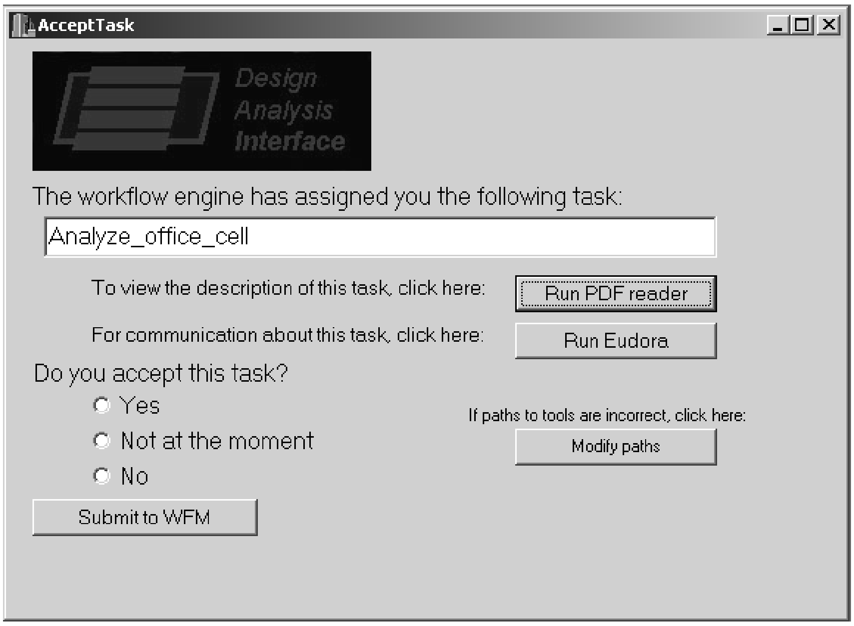


Figure 6.8: Message and navigation screen, activated by the workflow engine (example: task assignment)

Note that the messages and navigation screens appear as defined in the scenario. It is easy to modify the sequence, or assign tasks to other users. It is also possible (by defining a scenario with parallel tasks) for multiple tasks to appear at once, allowing the user to deal with those tasks at his own discretion.

Access to building performance assessment tools:
Within this scenario for selection of energy saving building components, the step of performance prediction requires the use of performance analysis tools to quantify the performance of different design options for different performance aspects. The current version of the DAI-Prototype allows analysis of three performance aspects: energy efficiency, thermal comfort and daylight autonomy of a single room. The DAI-Prototype has enabled these three analysis functions by means of internal interfaces to the thermal simulation tool EnergyPlus and the daylighting analysis tool IDEA-L. Although the DAI-Prototype is only a limited, proof-of-concept system, it allows to assess the performance of quite a few energy saving building components. In principle, all energy saving components that are a subsystem of the building façade (advanced glazing systems, blinds, climate façade/double façade, atria, glazed balconies, and even water walls, trombe walls or façade-integrated photovoltaic arrays) can be assessed using the present version.

The three analysis functions in the DAI-Prototype are relevant for the selection of energy saving building components. Of course the function describing the experiment to quantify energy efficiency is relevant for all design options that contain energy saving components. The function that quantifies thermal comfort is important for all cases where this aspect might become a constraint, for instance through the overheating of rooms with advanced glazing systems, skylights, double/climate façades or transparent insulation, and of atria, sunspaces and glazed balconies. Most of those energy saving building components also have an impact on the daylighting of rooms, making the third analysis function relevant as well.

In the current version of the prototype, the analysis functions need to be populated manually. To support his task an Analysis Function Interface appears for each of the different analysis functions. Figure 6.9. shows part of this interface. This interface only calls for the building design information that is absolutely necessary to analyze the energy efficiency (in other words, it pulls the essential data from the building design information layer and prepares it for submission to the tool layer). Note that part of the information gathering can be automated if structured, digitalized building design information is available on the information layer (which has not been attempted in the prototype).

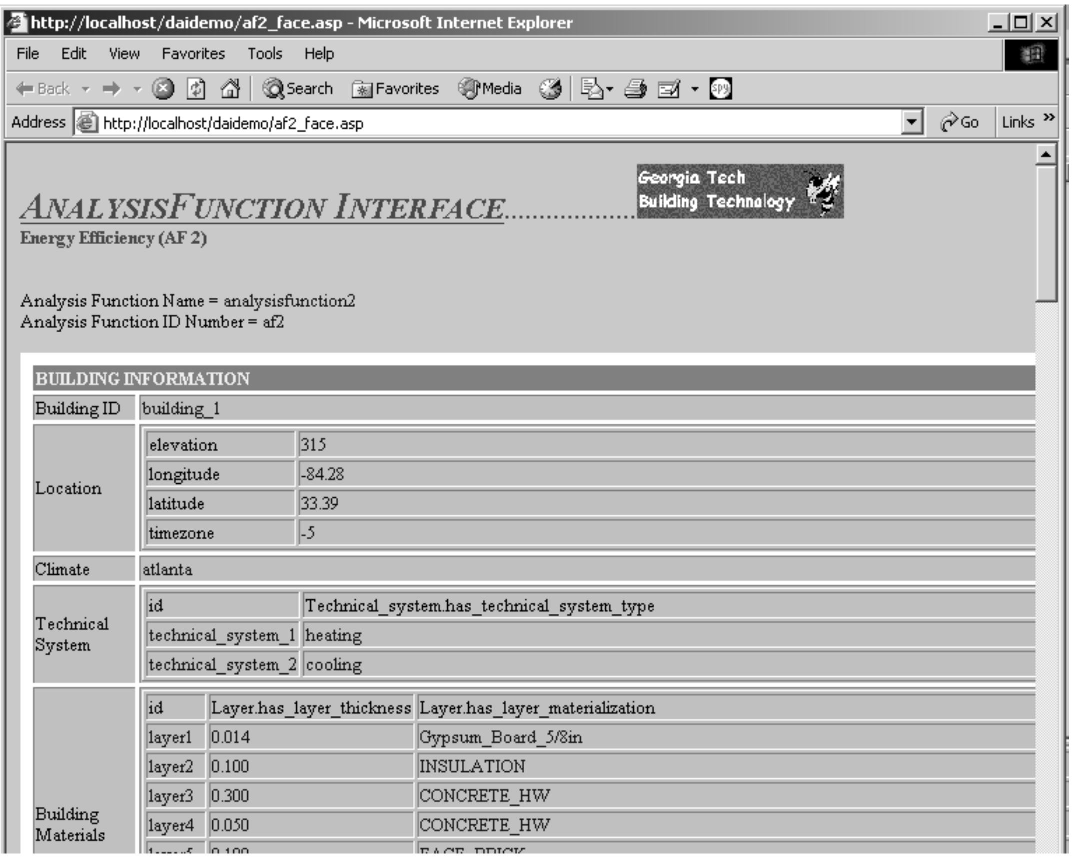


Figure 6.9: Analysis Function Interface for analysis function 2 (energy efficiency)

Once the analysis function has been populated and contains all information, the data can be shipped to the building performance analysis tool (in case of the analysis function for energy efficiency this is currently EnergyPlus), and the analysis can be run. Once the analysis is complete, a message pops up that displays these results. See figure 6.10 for an example. Results can also be stored in a database that keeps record of all results, or even inserted into a standardized report.

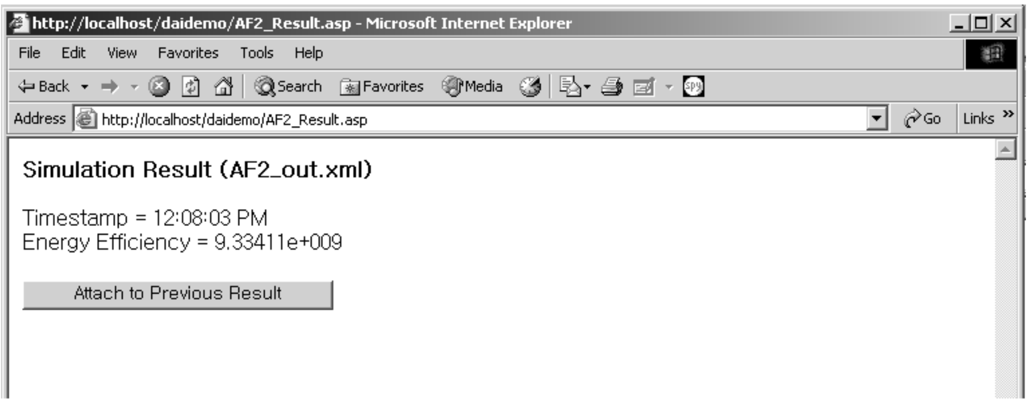


Figure 6.10: Reporting screen, showing that an analysis has been terminated successfully (example: analysis function for energy efficiency).

Note that the use of the concept of analysis functions minimizes the effort needed for modeling and simulation.

Additional support that can be embedded in the DAI-Prototype:
The workflow enactment of the scenario for selection of energy saving building components can also allow the DAI-Prototype to provide access to other support instruments (for instance the specific options that have been identified in chapter four). An example is presented in figure 6.11.

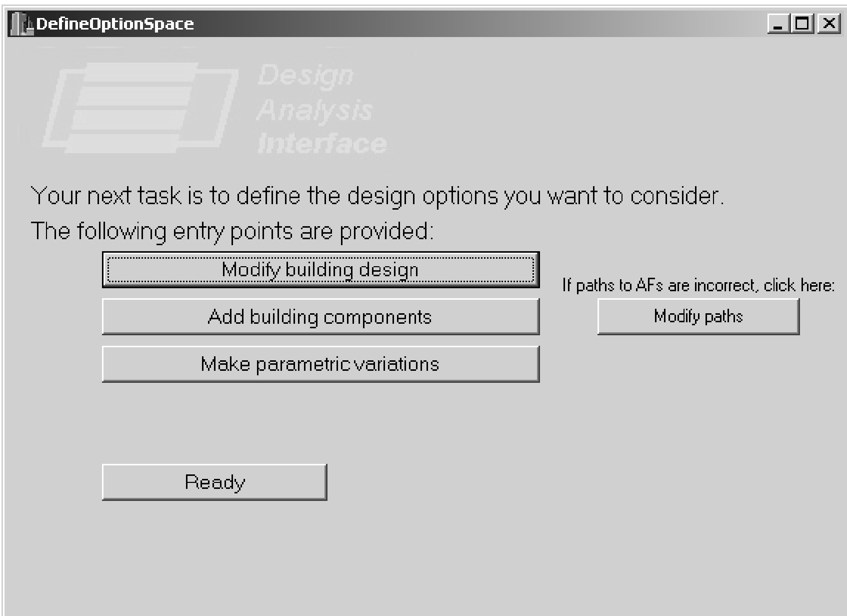


Figure 6.11: Message and navigation screen, allowing access to other support instruments (example: pre-selection of energy saving components)

In this case the specific message requests the user to pre-select (energy saving) building components, which during a next step will be used to define design alternatives by making combinations of a given building design and these pre-selected components. In order to support this task the navigation screen allows to access a database with energy saving components and an overview of monitored/evaluated demonstration projects through the button of 'add building components'. The components that are included in the database can be presented in groups, one of these groups being energy saving building components. Within this group, components could be accessed in two different ways: they might be viewed alphabetically (which is convenient if an expert-consultant wants to directly select specific components), or they might be presented in the form of a morphological chart[41] (which is more convenient if the user is searching for components to fulfill a specific function, but has no specific components in mind). An additional overview with demonstration projects might give the user access to projects with (energy saving) components that might inspire his pre-selection, closely supporting the current way of selecting components as observed in chapter three. Such a database should only contain evaluated and/or monitored projects (Fay, 2002), for which the contribution of individual components has been quantified; this will provide the user of a first, crude indication of what might be expected from using the same component in a similar project.

As only a limited DAI-Prototype is available, it is not yet possible to demonstrate the DAI-Workbench working in real building design practice and study the impact on the selection of energy saving building components. However, a number of relevant observations can be made on the advantages of using a DAI-Workbench over the current way of selecting these components:

- the DAI-Workbench facilitates the selection of energy saving building components according to the approach that was developed in chapter four.
- the concept of analysis functions in the DAI-Workbench allows for direct access to relevant analysis tool functionalities, minimizing modeling and simulation efforts.
- the DAI-Workbench is a support environment that allows to add support to other analysis-related tasks as well.

Note that except for the analysis functions as developed in the DAI-Initiative, none of the supporting instruments that might be used to further support the procedure is currently fully available. The DAI-Prototype is a first generation demonstration prototype only. Further developments should first of all include the development of a larger set of applicable analysis functions. These should cover the relevant performance aspects of buildings, and allow easy access to the main physical modeling principles. Moreover, they should also be connected to suitable computational tools on the tool layer. Only when the set of analysis functions reaches a certain critical mass an uptake of a DAI-Workbench by practitioners in the field of building design can be expected.

Remarks of the viability of the DAI-Prototype in a broader context:

The DAI-Prototype itself has been developed to demonstrate how building performance analysis can benefit from a process-centric approach, and how analysis functions can be used to connect the process with relevant tool functions. It also shows how the analysis functions can help to supply tools with the essential data needed to do a specific type of analysis.

[41] See 4.3.2: A morphological chart list essential functions of a design under development, adds the means by which these functions might be achieved, and allows to combine different means to achieve all functions and thereby define possible options for a design project.

Finally, the prototype conveys the flavor of future support environments that are geared towards internet-based teamwork.

The DAI-Prototype has been presented to the user community during a workshop in at the Lawrence Berkely National Laboratory in Washington on September 7th, 2002. See figure 6.12. In general terms the user community affirmed that the process centric approach can be useful, especially if this allows to define analysis procedures in a more rigorous manner and allows to apply some form of quality assurance. However, the workshop also identified a number of issues for future research and development:

- is it indeed possible to define a sufficient set of analysis functions for most design analysis interactions?
- what is the borderline between specific analysis functions? How far does parametrization of analysis functions go?
- can the DAI-workbench also be expanded to cover building life cycle issues?
- what kind of analysis results are actually needed by building design teams?

Figure 6.12: Presentation of the DAI-Prototype, LBNL Office, Washington

While the DAI-Prototype serves well to demonstrate how the strategy for selection of energy saving building components can be harnessed in a novel type of support environment, it is important to note that this prototype has limitations. Two important issues are the following:

- Clearly full computational support for the selection of energy saving building components can only be achieved if the DAI-like tools can be developed that contain a set of analysis functions that covers all possibly relevant performance aspects for buildings with such components, plus qualifying tools and interfaces from analysis functions to those tools. This requires further elaboration of the concept of analysis functions, and a proof that indeed a set of analysis functions can be developed that covers most typical analysis requests concerning energy saving building components. It is also important that the analysis tools in a DAI-like environment can actually deal with specific components like

heat pumps, co-generation units, blinds etc. It is obvious that development of a fully operational DAI-Workbench still requires major research and development efforts.
- The DAI-Prototype focuses on design teams that consist of several members, including an expert consultant. This limits the use of the workbench to design projects that do have corresponding design teams, and leaves out projects that are developed by single-actor teams (for instance many housing projects, designed by architects only). The argument can be made that such single-actor teams are not very likely to employ building performance analysis tools in current practice either, while that type of project is more driven by efficiency and economical market incentives (see e.g. Griffits and Zoeller, 2001). Still, the current version of the DAI-Prototype seems overly complex for that type of project and design team.

6.3. Discussion and Conclusion

The main goal of this chapter is the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, and the development of a substantiating prototype that demonstrates the feasibility of this strategy. The development of both the strategy and the prototype have been realized through participation in an international research project: the Design Analysis Interface DAI) Initiative (Augenbroe and de Wilde, 2003; Augenbroe *et al.*, 2003; Georgia Institute of Technology, 2003).

In this chapter a strategy for the selection of energy saving building components has been developed that defines the steps needed for a well-founded choice of these components. This strategy fits well with ongoing efforts in the field of building design management to develop systematic approaches to the building design process that ensure a cycle of analysis, synthesis and evaluation (see e.g. Eekhout, 1997, Brouwer, 1998, Best and De Valence, 2002). On the one hand the strategy ensures a number of important steps in the design decision-making process; on the other hand it does not impose a pre-defined way of working on the design team. In other words: it brings in the rigor of sound decision making where needed, while leaving open other aspects of the process to the preferences of the individual actors.

As proof-of-concept of the strategy the chapter presents the development of the DAI-Prototype. This prototype demonstrates how the strategy for selection of energy saving building components can be harnessed in a novel type of support environment. However, being the product of a research project, it also comes with limitations: the DAI-Prototype focuses on support for building design projects that employ expert consultants, and it is geared towards support for typical analysis tasks (recurring analysis work). These limitations do not apply to the strategy, but are essential to the field covered by the prototype.

The research steps described in this chapter result in the following conclusions:
- The ideas on improvement of the selection procedure for energy saving building components (chapter four) and on improvement of tools to better support such a procedure (chapter five) provide a basis for the strategy development. However, these ideas do not yet provide a solution for accessing suitable, reverse-engineered building analysis tools.
- The DAI-Initiative has introduced the concept of analysis functions to define a clear relationship between analysis processes and the actual use of analysis tools. Analysis functions define what analysis work is needed, in the form of: 'predict the performance of building (sub)system A for performance aspect B under conditions C, according to

measurement protocol D and assuming the aggregation E of observed states'. Analysis functions can be incorporated in an analysis process.

- Based on the ideas of chapter four and five and on the concept of analysis functions from the DAI-Initiative, the following strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components has been developed:
    - Energy saving building components should be selected according to a procedure that consists of definition of an option space, identification of relevant functions, specification of performance indicators, prediction of performance for all options and all performance indicators, evaluation of predicted performance and selection of the most desirable option.
    - Availability of time and expertise for modeling and simulation work are the most important limiting factors that hinder the application of existing building performance assessment tools for supporting selection of energy saving building components. In order to overcome this problem the analysis request must be stated unambiguously. At the same time, building performance analysis tools must be pre-conditioned (reverse-engineered) in order to meet these specific analysis requests.
    - The procedure for the selection of energy saving building components must be supported by a support environment that contains the relevant analysis functions, as well as a set of analysis tools that qualify for these analysis tasks. The support environment should also provide other support functions for the selection procedure.
- The viability of this strategy has been demonstrated by the development of the DAI-Prototype. This prototype has the form of a workbench that contains four layers that manage different aspects of the design analysis integration. The scenario layer of the workbench allows the design and enactment of analysis processes. For all activities in those processes that actually need to call building analysis tools an entry point has been defined by the development of analysis functions that match a pre-defined building analysis model with a suitable tool. The building analysis models are situated on a building model layer, while the computational tools reside in a tool layer. The (conceptual) building model can then be populated from an information layer that contains all building design data. However, this layer is only conceptualized in the prototype.
- The DAI-Prototype demonstrates how the strategy to provide computational support for selection of energy saving building components can be harnessed in a proof-of-concept software support environment. It has been demonstrated that the prototype:
    - allows definition and enactment of a rational selection procedure, enforcing relevant steps while maintaining flexibility;
    - provides better access to appropriate analysis tools and models;
    - minimizes problems related to data exchange;
    - supports the modeling and simulation tasks, though a need for expertise remains;
    - shows how automation of design analysis interaction can be maximized, thereby showing how analysis costs (especially in the field of modeling) can be reduced.
    - provides the prospect that better communication between design and analysis will in the long term result in an increase of trust in computational results.
- The DAI-Prototype is intended to provide support for analysis work by expert consultants. However, one could also take a broader scope and add support for design work, modeling work etc by other actors (architects, project managers, …) in the design process as well. Whether or not this is desirable and/or feasible is a matter of future research.
- Support environments like the DAI-Prototype are not simple systems. Substantial investments in future research and development will be needed if such systems are to be

actually produced for the building industry. There is a need to identify which tasks are to be supported by such environments, and how to support those tasks (in terms of DAI: to identify the typical analysis requests, analysis functions and links to tools). However, it is important to note that:

- the inclusion of the process dimension (workflow management) provides an area where a number of large industrial players in the field of workflow management systems (e.g. IBM) can open part of the AEC-industry for their products, which currently only has a very limited uptake of such systems but which can greatly benefit from introduction of workflow management systems and the related case handling systems [42] (see e.g. van der Aalst *et al.*, 2003).
- DAI-like support environments act as an interface between building design and a whole set of suitable analysis tools, thereby supporting different products from different developers of analysis software. This might create a common base to finance the development of such a support system.
- efforts like the DAI-Initiative try to build a bridge between the many years that have been invested in the development of building product models like the IAI-IFC and are probably a pre-requisite to obtain a return on these investments.

- Future work on the integration of building simulation and building design requires further development of support environments that capture and support the analysis process, and that provide access to tools that are able to support relevant process steps. Reverse-engineering of analysis tools to match specific analysis tasks seems an important step in order to increase the applicability of these tools.

While research and development efforts on better integration of building design and building simulation continue, it is important to discuss what people working on tomorrow's design projects can contribute towards more rational decision-making regarding the selection of energy saving building components and better integration of design and simulation. This thesis and chapter are concerned with providing support for the future design team, yet also leads to a number of recommendations for today's architects and consultants. These recommendations will lead architects and consultants to make a start towards more rational decision-making and provide good starting conditions for computational support for the selection of energy saving building components.

- Architects:
  - can start formulating analysis requests as selection problems:
    Architects can play a key role in initiating rational decision making on the selection of energy saving building components by stating part of their questions for consultants explicitly as 'selection problems'. To this end, they should actively contribute to the development of an option space. Architects are in the perfect position to help develop an option space that consists of several design alternatives that can be compared. So far the trend seems rather to develop one design and ask for feedback of an expert consultant; architects should be aware of the impact this has on the extent of the analysis work.
  - can input information on relevant functions and criteria:
    Since architects are doing the actual design work, they have the best overview of aspects of the design they consider important. It would be beneficial for the selection of energy saving building components if they state these different aspects

[42] Workflow systems have limitations, especially in the field of modifications of the workflow design during ongoing processes; work in the field of case handling tries to overcome these limitations but is only just emerging.

to their partners in the decision making process, thereby steering towards multi-criteria decisions. Architects could also provide useful input by providing as much information on their perception of the 'virtual experiment' that is needed during analysis work (like expected user behavior, climate conditions etc). Architects should familiarize themselves with some basis aspects of performance indicators, helping them to communicate with consultants.

- Consultants:
    - can contribute to the development of an option space:
      With their experience on different projects consultants too can very well contribute to the design of option spaces, suggesting alternatives (energy saving building components) that might be viable options but are not known to individual architects
    - can improve the communication on virtual experiments:
      Consultants are in full control of all tool settings, and therefore of the virtual experiments that can be carried out with these tools. By entering a deeper discussion with architects on what virtual experiment bests meet the analysis needs, they can create an opening to better matching the analysis needs of the architect with the analysis powers of the available simulation tools.

7. Closure

"Trials never end, of course. Unhappiness and misfortune are bound to occur as long as people live, but there is a feeling now, that was not here before, and is not just on the surface of things, but penetrates all the way through: We've won it. It's going to get better now."

(Robert M. Pirsig)

The general problem addressed in this thesis is integration of computational tools and the building design process. Within this field, the work has focused on the selection of energy saving building components. Energy saving building components play an important role in efforts to reduce the impact of the built environment on global energy use. However, their performance is often difficult to predict due to different underlying principles, impact on different performance aspects and dependency on interaction with the building. Computational tools might play an important role in the selection of energy saving building components, but there are serious concerns about the actual support provided by existing tools in building design practice. Yet there are good reasons to strive for integration of computational tools and building design process: they can provide detailed performance information for buildings that still have to be constructed and they allow comparison of different design options under identical conditions.

The goal of the research presented in this thesis has been the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components. The following main research questions have been identified as providing the key towards achieving this goal (see paragraph 2.5):

- What is the current way of selecting energy saving building components during the design of energy-efficient building projects, and how adequate is this?
- To what extend are existing building energy simulation tools used during the selection of energy saving building components, and to what end? How adequate are these existing tools?
- How can the current way of selecting energy saving building components be improved?
- How can existing building energy simulation tools be improved? And what effect can be expected from ongoing developments and integration efforts?
- How can improvements of the way of selecting energy saving building components and improvements on the part of tools be combined into a strategy to provide computational support for selection of energy saving building components?
- Can a prototype be developed that demonstrates how the proposed changes actually lead to better integration of design and simulation, and hence to improved computational support for design decisions with respect to the selection of energy saving building components?

In this final chapter paragraph 7.1. provides an overview of all research activities conducted in this research project. Paragraph 7.2. presents the conclusions from these research activities, thereby answering the main research questions. Paragraph 7.3. identifies issues that deserve further attention, pointing out aspects for future research. Paragraph 7.4 presents the closing remarks that conclude the thesis.

7.1. Overview

The work presented in this thesis consists of four main research activities, all focusing on the use of simulation tools to support the selection of energy saving building components: analysis of current energy-efficient building projects; development of an approach for well-founded selection of these components; analysis of the suitability of existing tools to support the selection process, and development of ideas for improvement of these tools; and development of a strategy as well as a proof-of-concept prototype that provides support for the selection of energy saving components and that demonstrates the viability of the proposed changes.

The analysis of current energy-efficient building projects was initiated by a lack on unbiased information on the way in which energy saving building components are selected in current practice, and lack on information of the role of computational tools in this selection process. The goal of the analysis was to find out for recent prestigious building design projects in the Netherlands how this selection took place, and what role tools played in supporting that selection.
In order to attain this goal three case-studies and a survey were conducted. The case-studies provided in-depth information on three projects. The survey demonstrated the representative ness of the cases for a larger sample of prestigious energy-efficient buildings. The overall finding is that in current projects, computational tools do not play an important role in the selection of energy saving building components, since these tools are used in later phases than those relevant for the selection, and are only used for different purposes (optimization and verification rather than to support choices). Hence there is a need to improve both the selection procedure as well as the tools that support that selection.

The development of an approach for well-founded selection of energy saving building components had as goal to improve the current way of selecting these components. Requirements and constraints for making a well-founded choices have been identified and used to assess existing theories for making design decisions. An approach for performance-based selection of energy saving building components has then been developed, using applicable elements from existing theories to define the essential steps. The viability of the resulting approach has been demonstrated through application of the approach to an example.

The analysis and improvement of tools for the selection of energy saving building components consisted of the following steps: analysis of the different main categories of tools and their role in supporting the selection of energy saving building components, and assessment of existing tools as well as identification of possibilities for improvement of the two most important categories (analysis tools and support environments). Analysis tools can be improved through reverse-engineering, which clarifies the building design alternatives and performance indicators that can be handled by these tools. Support environments need to contain embedded analysis tools as well as a selection mechanism that helps users to find a suitable tool for an analysis job.

Participation in an international research project, the Design Analysis Interface – Initiative, provided the final elements needed for completion of this research project: the development of the strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components and the realization of a substantiating prototype that shows the viability of this strategy.

A strategy for selection of energy saving building components has been developed in this thesis consists of the following elements:

1. Energy saving building components should be selected according to a procedure that consists of definition of an option space, identification of relevant functions, specification of performance indicators, prediction of performance for all options and all performance indicators, evaluation of predicted performance and selection of the most desirable option.
2. Availability of time and expertise for modeling and simulation work are the most important limiting factors that hinder the application of existing building performance assessment tools for supporting selection of energy saving building components. In order to overcome this problem the analysis request must be stated unambiguously. At the same time, building performance analysis tools must be pre-conditioned (reverse-engineered) in order to meet these specific analysis requests.
3. The procedure for the selection of energy saving building components must be assisted by the use of a support environment that provides a mechanism that allows users access to different (embedded) building performance assessment tools for doing specific analysis tasks.

The prototype development demonstrates how the proposed ideas for a selection procedure and for improvement of analysis tools and support environments lead to better integration of design and simulation, and thereby show the viability of these ideas to provide improved computational support for the selection of energy saving building components.

7.2. Conclusions

The research efforts presented in this thesis have resulted in the following main conclusions:

- In current energy-efficient building projects most energy saving building components are selected based on analogy: use of similar components in previous buildings by the architect or consultant, or on the use of these components in demonstration projects. It appears that decision-making on energy saving building components is based on simple, heuristic decision rules.

- Because of the complex interactions between building and energy saving building component(s), the impact of energy saving components on different performance aspects (energy efficiency, thermal comfort, daylighting, acoustics, …), the many different underlying principles of these components and the fact that the set of possible combinations of building and energy saving components is infinite, it seems preferable to apply multi-criteria decision rules to the selection of these components, ensuring that different requirements are considered in the decision-making process.

- In current building projects, computational tools fail to impact the selection of most energy saving building components: most of these components are selected during the design phases of feasibility study and conceptual design, while most computational results do not materialize before the phase of preliminary design. Moreover, computational tools are used for optimization and verification purposes rather than to support choices.

- The development of new building energy simulation tools shows a continuous increase of capabilities and complexity. However, this trend increases the dependency on adequate modeling and expertise, and thereby increases the barriers to integration of building design process and building simulation even further. It therefore is concluded that efforts to improve the adequacy of tools to support building design decision-making should focus at making the modeling and simulation process more transparent.

- There have been many efforts that aimed at facilitating modeling and simulation work by means of default values, special user interfaces that hide complexity, etc. Yet these efforts do not seem to have resulted in better integration of building simulation and building design process. This is probably due to the fact that the resulting tools do not meet the requirements of accommodating specific building design options and of providing the specific information as requested for the design decision at hand. It is concluded that a better alternative to simplification, hiding or automation of tool functionalities can be found in the option of subdividing tool functionalities in small but relevant modules that meet specific design analysis needs (and which can be called where needed only). This requires reverse-engineering of tools to find and access these modular tools functions.

- A procedure for the selection of energy saving building components can be developed using existing knowledge from different engineering domains, resulting in a performance-based approach for the selection of these components. This approach rationalizes the selection procedure, and makes the role of subjective assessment explicit. Since it is based on performance prediction, it provides an optimal base for the use of computational tools.

- There are different categories of tools that all play a role in supporting the selection of energy saving building components: design tools, modeling tools, analysis tools, support environments, and 'others'. Of these, analysis tools and support environments are the most important ones when it comes to supporting a well-founded choice of these components.
  - Existing analysis tools have been found to be able to support the performance-based selection of energy saving building components. However, due to the need for expert intervention to tune the tool to the specific analysis request, their operational use is limited. Improvement of these tools can take place by reverse-engineering of existing tools, providing accurate information on the building design alternatives and performance indicators that any specific tool can handle.
  - Support environments are mostly still in an experimental stage. They can be improved by embedding different alternative tools in one environment and including a mechanism that support users in selecting the best tool for specific tasks.

- A prototype of a Design Analysis Interface (DAI) - Workbench has been developed that demonstrates the feasibility of better integration of building analysis tools and building design process through the use of a layered, process-centric approach. Though still limited in scope, this prototype shows that the approach allows to provide improved computational support for the selection of energy saving building components. The concept of analysis functions links the analysis process with analysis tools by matching analysis task and tool capabilities.
  The DAI-Prototype focuses on design teams that consist of several members, including an expert consultant. This limits the applicability of the workbench to corresponding projects; however, these projects are those that are most likely to involve use of building performance assessment tools.
  Clearly full computational support for the selection of energy saving building components can only be achieved once the DAI-Prototype contains a set of analysis functions that

covers most relevant performance aspects for buildings with such components, plus qualifying tools and interfaces from analysis functions to those tools.

- Future work on the integration of building simulation and building design requires further development of support environments that capture and support the analysis process, and that provide access to tools that are able to support relevant process steps. Reverse-engineering of analysis tools to match specific analysis tasks seems an important task in order to increase the applicability of these tools.

- Today's architects and consultants can already make a start towards more rational decision-making regarding the selection of energy saving building components and provide a context that allows maximal chances for the use of simulation tools to provide computational support. Architects can help by formulating analysis requests as 'selection problems', actively contributing to the development of an option space, providing as much input as possible on relevant functions and criteria, and by familiarizing themselves with basic aspects of performance indicators, helping them to communicate with consultants. Consultants can also contribute actively to the development of an option space, and can help communication by discussing virtual experiments in more detail, steering towards a better match between analysis request and tool functions.

7.3. Future Challenges

The following research questions have been identified as being relevant for further research:

- *Does real-time observation of ongoing design processes reveal other additional insights into the way energy saving building components are selected? What additional factors (social interaction, group behavior, politics) influence decision making on the selection of energy saving building components? Is it possible to identify relations between the way building design projects proceed, the resulting building designs, and even the performance of the resulting building?*

  The research presented in this thesis has studied the selection of energy saving building components from a technical point of view, and through retrospective analysis only. However, it is clear that the above-mentioned social issues have a large bearing on the final decisions made in any design process. Further research is needed to take these aspects into account. It would be very interesting and informative to see whether some link between process, design and final product can be established.

- *What information (about background, integration aspects, performance, ...) would design teams want to have about energy saving building components?*

  This research question takes another path for re-structuring the building design process, complementing the work presented here. Instead of using existing theories to define what design teams *should* consider in the process of selecting energy saving building components (technology-push), this question addresses what the design team itself *would like* to know (technology-pull).

- *What are the option spaces and performance aspects covered by the existing building performance simulation tools? And how do these relate to the option spaces and performance aspects one would like to cover?*
  This thesis has taken a limited view of decision-making in building design, only discussing the selection of energy saving building components, and only assessing one exemplary tool for one case. However, further studies to find out the match and mismatch between the analysis requirements from a building design point of view and the capabilities of the existing tools definitely is an important issue.

- *What is the effect of combining the uncertainties in building design (due to incompleteness of the design) with uncertainty in building performance assessment (due to modeling, computational procedures etc)?*

  In this thesis the use of building performance prediction by computational tools in the design process has been described without the consideration of uncertainties. Yet it remains unclear how the combination of uncertainty in the building design itself and uncertainty in the performance assessment add up for the total performance prediction. Further research to define these borders for the use of computational tools is urgently needed.

- *Is it possible to develop evolving building models that match the development of a building design?*

  On the crossroads of process management, product modeling and tool development, the development of tools that can be used in different stages of one and the same design process seems challenging. However, due to the interrelation of different performance aspects, data structures etc, this probably is a difficult issue.

- *Apart from their role as analysis instruments, what role can building performance simulation tools play as design tool, helping the design team to generate building design variants?*

  So far, efforts have focused on using simulation tools to support decision making in the building design process. However, there also is the option to use these tools to help design teams to come up with viable design alternatives. A different type of research could explore and enhance the role of simulation tools in this field. Some first projects in this direction have been initiated by Yannas (2003) and Mahdavi (2003).

7.4. Closing Remarks

The main goal of the research presented in this thesis, the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, has been achieved. A prototype shows how the strategy can be harnessed in a new generation of interfaces between building design process and building analysis. However, it must be noted that introduction of fully functional workbenches in building design practice still requires a lot of research and development efforts.

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List of Abbreviations

AF	analysis function
BP	design phase of building preparation
CAD	computer aided design
CD	design phase of conceptual design
CE	concurrent engineering
CFD	computational fluid dynamics
COMBINE	COmputer Models for the Building INdustry in Europe (research project)
COP	coefficient of performance
DAI	Design Analysis Interface (research project)
DFM/A	design for manufacture and assembly
DOE	Department of Energy (USA)
EDAS	Energy Design Advice Scheme
EKS	Energy Kernel System (prototype tool by University of Strathclyde)
EPC	energy performance coefficient
EPN	energy performance regulation (Netherlands, abb of 'Energie Prestatie Norm')
ESBC	energy saving building component
FD	design phase of final design
FS	design phase of feasibility study
HTML	hypertext markup language
HVAC	heating, ventilation and air conditioning
IDEF-0	Integral DEFinition process modeling method
IAI	International Alliance for Interoperability
ICT	information communication technology
IFC	International Foundation Classes, product model developed by IAI
IDM	Integrated Data Model, product model as developed in COMBINE
IEA	International Energy Agency
IFE	Intelligent Front End (prototype tool by University of Strathclyde)
IIBDS	Intelligent Integrated Building Design System (prototype tool by University of Strathclyde)
IPD	integrated product development
PAM	performance assessment method
PD	design phase of preliminary design
PI	performance indicator
PLEA	Passive and Low Energy Architecture (organization)
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
PTM	performance test method
PV	photovoltaics
QFD	quality function deployment
STEP	standard for the exchange op product model data
TMY	test meteorological year
TRY	test reference year
UNEP	United Nations Environment Programme
VE	value engineering
XML	extensible markup language

Glossary

analysis function	defines the experiment needed to generate states that can be observed and analyzed to derive the functional performance of a system for a given performance aspect
analysis scenario	a process describing the steps and relations between those steps that must be taken in order to analyze the (performance of) a building
analysis tool	tool that is used to assess properties and/or performances
building product model	digital building representation and other digital information about a building
building design	the activity that results in detailed drawings and technical descriptions of a building that will satisfy a brief which indicates goals, requirements and evaluation criteria
building simulation	reproduction of the physical behavior of buildings and building (sub)systems, based on physical modeling of the system, development of mathematical equations that describe the behavior, solution of these mathematical equations, and presentation and visualization of the resulting output. The most relevant behavioral aspects studied in building simulation are heat transfer, (day)lighting, acoustics, and air flow.
design analysis request	formal request to analyze the performance of a building or building sub-system for a (set of) building performance aspect(s)
design team	the set of actors that work together in a building design project; mostly consisting of an architect and a number of specialized consultants (HVAC, building physics etc)
design tool	tool that uses the computer to generate design alternatives, helping to modify and improve on existing building designs
energy saving building component	measure or features that makes buildings more energy-efficient that materializes in the form of a distinct component; ranges from general principles (for instance compact building form or zoning) to specific, of-the-shelve systems (for instance heat pumps and solar collectors)

modeling tool	tool that allows the use of computers to represent the evolving ideas of a building as an artifact during the design process by capturing relevant information like dimensions, shape, materialization etc
morphological chart	tool that lists essential functions of a design under development, adds the means by which these functions might be achieved, and allows to combine these different means to achieve all functions and thereby define possible options for a design project
option space	set that contains all alternative (design) options that are considered
parametrization	description of an option space based on the identification of key parameters that are subject to change
performance aspect	field of action for which the building is to perform a required function (e.g. energy efficiency, thermal comfort, etc)
performance indicator	a value or set of values that quantifies performance (from a functional point of view) of a system for a given performance aspect if subject to a given experiment
performance ontology	overview of possible building functions and related performance aspects
product model	see: building product model
renewable energy	energy that is not gained from fossil fuel, like solar energy, energy from ambient sources, wind energy, energy from biomass, hydropower and geothermal power
reverse-engineering of tools	providing accurate information on the building design alternatives and performance indicators that a specific tool can handle
systems engineering	application of the scientific method to the design, development, implementation and control of systems
support environment	system or tool that provides functionalities that support the use of other tools, such as easy access through (standardized) interfaces to embedded tools, coupling of tools, use of shared information repositories, etc

workflow management system	automated system that support process management in complex situations, allowing routing of information through organizations, task assignment, progress monitoring etc

Appendix A: Overview of Energy Saving Building Features and Components

This appendix provides an overview and brief description of the most common energy saving building components and features that are currently used in building projects. The overview is not claimed to be complete, but is added to give an indication of the many components and features that are available. The list is ordered alphabetically.

Advanced glazing system:
Openings in the building shell that are filled with glass allow solar radiation to enter the building, but also result in energy losses due to transmission through the glazing material. Different advanced glazing systems try to control both solar access and transmission losses through techniques like super-insulating triple glazing, special fillings or screens in the cavity, coatings on the glass, and special frames.

Air-tightness features:
In order to reduce energy losses by infiltration porches, draught or weather strips and other measures that increase the air-tightness of the building can be applied.

Ambient heat source:
Using advanced technology, specifically heat pumps, it is possible to use ambient heat sources like outside air, groundwater or rain as renewable energy source for HVAC-systems.

Atrium (see sunspace):
An atrium is a large space in a building that has a glass roof. This allows solar access deep into the building, while air from the atrium, preheated by the sun, can be used for ventilation purposes. Depending on their specific lay-out atria can be more or less isolated from the building; see sunspaces for further discussion.

Aquifer:
An aquifer is a layer of rock or soil underneath the surface of the earth which holds water; aquifers can be used to store pre-heated water for seasonal shifts (inserting warm water in the summer and extracting this water in winter), or as a source of water for cooling purposes.

Black attic:
A black attic is a rare system that consists of an attic with a large, solar-oriented glazed aperture; air is heated inside this attic and then distributed to the building by means of forced ventilation.

Blinds:
(Venetian) blinds help control solar access; they are important in preventing overheating and thereby have a strong impact on reducing cooling loads.

Building energy management system (BEMS):
Intelligent operation of the HVAC-system, control of lighting, blinds etc can have a large impact on overall energy use. A computer system that is provided with information on climate conditions, information about operational conditions inside the building and that uses this information for efficient control is named a building energy management system.

Ceramic building elements:
Ceramic building elements are masonry units; they can contain an air cavity, resulting in increased insulation values.

Chemical storage:
Materials that undergo a change of phase at a given temperature can be used to store or retrieve energy. Rarely used in real building projects, mostly only an experimental component.

Clerestory / skylight:
A skylight allows solar access through the roof of a building to parts of the buildings that are too far from the façade to receive solar irradiation in the normal way.

Climate façade:
A climate façade is a glass façade that includes a mechanical ventilated cavity. Mostly the cavity also contains (Venetian) blinds. Closely related to double façade. In case only a part of the façade is made of glass, this is named climate window; in case the façade is horizontal it is named a climate roof.

Cogeneration unit:
A mechanical system that produces both steam and electricity at the same time; the steam can be used as source for heating or as driving force for different types of equipment. Cogeneration units make maximal use of consumed (fossil) energy.

Combined boiler:
A so-called combined boiler allows to heat water with both a conventional burner as well as through a solar collector. Mostly used in houses.

Compact building design:
By maximizing building volume while minimizing the building shell area building designers can try to minimize the impact of transmission losses.

Concentrating solar collector:
Concentrating solar collectors use an optical device between the source of solar radiation and the absorber. This allows to deliver energy at higher temperatures than would be possible without this device.

Cooling ceiling:
A cooling ceiling is like a horizontal radiator through which cold water is circulated. Cooling ceilings are supposed to be more energy-efficient than the usual air-conditioning systems that supply pre-cooled air to rooms.

Daylight-responsive artificial lighting:
A system that controls the operation of the artificial lighting depending on the amount of daylight available in the room.

Displacement ventilation:
Ventilation system that inserts ventilation air at a sufficient pressure to minimize infiltration losses.

District heating:
Heating system that heats more than one building, which allows to achieve higher efficiency than single systems.

Double façade:
A climate façade is a glass façade that includes a cavity with natural ventilation. Mostly the cavity also contains (Venetian) blinds. Closely related to climate façade.

Earth storage:
Use of soil to store energy in order to accommodate day-night or seasonal shifts between energy production and energy consumption. Mostly the ground under the building is used, sometimes a special earth wall is erected. Often the earth storage holds a transport system for energy as well, like air or water ducts.

Energy-efficient appliances:
Energy efficiency of a building of course also depends on the appliances in the building. Using energy-efficient computers, faxes, washing machines or even elevators etc helps reduce the energy consumption of the total building.

Energy-efficient HVAC system:
Heating, ventilation and air conditioning systems come in different types. Some of these are more energy-efficient than others. Systems that perform better than the average heating system, mostly coming at additional costs, can help reduce energy consumption of the building.

Energy-efficient hot-water system:
Another building system consuming energy is the system that provides hot water. This can be made more energy-efficient by using state-of-the art boilers, taking care of designing a short piping system, putting thermal insulation around pipes etc.

Energy-efficient lighting:
Artificial lighting is another system consuming energy. This can be made more efficient through the use of low-energy light bulbs and careful positioning of lights (only on positions where they are needed).

Energy pile:
Ram pile used for foundations that also includes ducts for circulation of water, which allows to access the earth around the piles as well as the thermal mass from the piles themselves for energy storage in the soil.

Evaporative cooling:
System that utilizes the energy extraction that goes with the evaporation of water in order to cool buildings. Can either work directly, like water evaporating from a roof, or indirectly, where some medium is cooled in a cooling plant.

Flat plate collector:
A type of collector that is used to capture solar energy and transfer this to a transport medium, usually air or fluid. This type of collector uses both beam and diffuse solar radiation. They do not require tracking of the sun, and are simpler than concentrating collectors, requiring less maintenance.

Flexible workplace:
Building feature that sees the employees of an office not having their own private workplace, but flexibly sharing workplaces. In offices where employees also do work outside the office (visiting customers etc) this can allow to reduce the number of offices / building volume required, thereby lowering overall energy consumption.

Floor heating:
System that heats the floor. Supposed to be efficient because of a uniform heat distribution, reducing draught.

Geothermal heat source:
Use of internal heat of the earth as source for heating. Can be accessed through aquifers.

Glazed balcony:
Energy saving feature that is often used in renovation projects, in which existing balconies are sealed with glass, thus providing an additional thermal barrier. Glazed balconies in fact become small sunspaces.

Heat exchanger:
HVAC-component that allows to transfer energy form one transport medium (fluid or air) to another. Often used to transfer energy from outgoing ventilation air to incoming air.

Heat pipe:
Heat pipes are solar collectors that consist of a an absorber that is placed in a glass envelope, mostly containing a vacuum; this reduces energy loss due to convection and conduction from the absorber to the outside.

Heat pump:
Heat pumps are HVAC-components that use mechanical energy to transfer energy from a source at a lower temperature to a sink at a higher temperature; used to obtain energy from sources like outside air and water, as well as for cooling (refrigerator).

Heat-absorbing glazing:
Glazing that allows transmission of light but blocks out thermal radiation, thus reducing the cooling load of buildings.

Heated ceiling:
Horizontal radiator, just like a cooling ceiling; this time however it is used for heating. Supposed to be efficient because it allows to provide (radiative) heat close to workplaces that cannot be reached by radiators (radiators are mostly positioned near façades and walls).

HF-lighting:
A specific type of energy-efficient fluorescent lighting (high frequency system).

High temperature cooling:
Cooling system that utilizes a relatively warm cooling medium, thereby reducing the loss related with cooling this medium.

Holographic optical element:
Holographic optical elements are a daylighting system that uses holography to redirect incoming solar radiation at the window, thereby allowing to light specific zones/locations in a room. This system has seen high interest, but few actual applications in real buildings.

Individual controls:
Individual controls of HVAC-systems, (day)lighting and appliances allow users to utilize those systems according to demand. If users take care to operate these systems only when needed this reduces energy consumption and increases the comfort experienced by the users, since they themselves are in control. However, if users do not make an effort at wise operation, this might result in increasing energy consumption.

Individual gauges:
In houses, individual gauges help to identify the energy use of each occupant, allowing to bill that occupant for actual energy use. This has proven to be an important incentive for people to change their energy consumption pattern, especially in comparison to collectively gauged houses/complexes.

Laser-cut panel:
A laser-cut panel is a clear acrylic panel in which small horizontal cuts have been made with a laser. These cuts are reflective and allow to redirect incoming daylight to the ceiling of a room.

Light shelf:
Light shelves are reflective elements that are positioned next to a window. They allow to redirect incoming daylight, mostly having the objective to allow solar access deeper into a room.

Light well / light shaft:
A light well or light shaft is a system that allows daylight to enter deep into a building by means of a light-reflecting duct. Mostly daylight is captured through an opening on the roof and brought into an internal room.

Lighting control with presence detection:
Artificial lighting can be equipped with a detector that monitors whether people are present in the room; this allows to turn of the artificial lighting and save energy when nobody is in the room.

Lighting row:
A lighting row is a set of skylights linked together, allowing daylight into a building through the roof. Often used in traverses/corridors.

Lowered air exchange rate:
By lowering the ventilation rate it is possible to reduce ventilation losses. However, a minimum ventilation rate is required for almost all spaces due to health reasons.

Low temperature heating:
Heating system that utilizes a relatively cold heating medium, thereby reducing the loss related with heating this medium.

Mezzanine:
Building feature that consists of making an opening in a floor to allow daylight to penetrate deep into the area below; a mezzanine also allows vertical coupling of different spaces.

Monitoring system:
A monitoring system logs data about operational settings and performance of a building, room or building sub-system. This can be a powerful instrument in achieving efficient operation of buildings and building systems.

Movable thermal insulation:
Thermal insulation material reduces transmission losses due to conduction. However, in some cases it is useful to allow transmission at certain times of the day/season/year, while reducing it at other times. Movable insulation is an option to gain this control.

Natural ventilation:
Air exchange caused by wind pressure differences and thermal differences is called natural ventilation. This is energy-efficient when compared to mechanical ventilation as is used in many buildings.

Nocturnal ventilation:
Ventilation with cold, outside air during nighttime can help to cool down a building, reducing the cooling load during daytime.

Optimized glazed area:
Glazed areas allow for solar access, but in most cases also result in larger energy losses due to transmission than normal walls. Optimized glazed areas balance both effects.

Overhang:
Overhangs are used to allow solar access in winter, but prevent solar access in summer. This way they maximize solar heating and minimize cooling load.

Photovoltaic cells (3 main types, net coupled and stand alone):
Photovoltaic cells convert part of the incoming solar radiation into electrical energy. The main types of PV are amorphous, polycrystalline and crystalline silicon. PV cells are mostly combined into arrays. As PV cells only generate electricity when solar radiation is available, an important issue is storage; some systems do not have any storage, others use batteries, and others supply energy to a power grid.

Plug-in gas connector:
In some cases appliances working on gas are more efficient than appliances working on electricity. In those cases specific plug-in gas connectors are an advantage.

Radiant heating:
Increased radiant heating allows to decrease the air temperature in a room, sometimes resulting in lower energy usage for space heating.

Remote storage wall:
A remote storage wall is a wall doubling as solar collector. Warm air from a cavity between the wall and glazing on the outside can be used to heat the adjacent building. For optimal control the glazing can be covered with thermal insulation material to reduce energy losses at night.

Roof pond:
A roof pond is an exotic building feature where a layer of water stands on top of the roof of a building This water can be used for heating or evaporative cooling; sometimes the roof pond has removable insulation.

Shutter:
A shutter is the traditional solution to cover windows at night with some form of movable insulation material.

Solar water heater:
A solar water heater is a solar collector used to increase the temperature of water.

South-facing windows:
Windows on the south are supposed to increase solar access, and thereby reduce energy consumption. However, this only is true if the transmission losses at night do not offset this solar gain.

Storage wall:
A storage wall is a wall designed specifically to store energy; mostly made from brick or concrete, sometimes also consisting of compartments that contain water (which has the advantage of allowing internal heat transfer not only due to conduction, but also convection).

Sun screen:
Sun screens are simple devices to prevent overheating due to unwanted solar access, thereby reducing the cooling load of buildings.

Sunspace:
A sunspace (also named conservatory, winter garden) is a space with a large percentage of glazing. Sunspaces can play different roles in making buildings more energy-efficient. The space itself can be used as room with solar heating only, which then can be used in spring and autumn. Depending on the construction separating sunspace and building, it is also possible to use the sunspace to preheat ventilation air. A sunspace also can function as porch and provide an additional insulation layer. However, once a sunspace gets heated in winter it can result in an increase of energy use. Also, the risk of overheating in summer must be considered.

Thermal insulation:
Thermal insulation material reduces transmission losses due to conduction.

Thermal mass:
Thermal mass (mostly concrete, brick, earth) can be used to store energy, thereby damping temperature fluctuations and decreasing heating and cooling loads.

Translucent insulation material (TIM) :
Translucent insulation materials are specific materials that allow transmission of light, while reducing conduction losses. Some examples of TIM are aerogel, multiple transparent foils, capillary glass structures and acrylic glass foam.

Trombe wall:
A trombe wall is a wall with high thermal mass (mostly brick/concrete) that has a glazed cavity on the outside. Incident solar radiation heats the wall and the air in cavity; both are used for space heating.

Ventilation with heat-recovery:
In order to reduce energy losses due to ventilation, energy from outgoing ventilation air can be transferred to the incoming air using a heat exchanger.

Water reservoir:
System containing a substantial amount of water, which is either useful as thermal mass in the building in order to control temperature fluctuations, or as storage for either hot or cold water in order to deal with time-shifts between the best time to heat/cool water, and the time when this water is needed to heat/cool the building.

Water turbine:
Use of the energy of flowing water to generate electrical power, or directly provide power to some mechanism. The traditional water wheel is an example, but modern variants include turbines in barrages or even turbines in rainwater drains.

Wind turbine:
Use of wind energy to generate electrical power, or directly provide power to some mechanism. Traditionally named windmill.

Zoning:
Feature that manages the energy use of a building by a clever lay-out of spaces. For instance, in houses it makes sense to include bathroom and living room (rooms that require high temperatures) in the core, while bedrooms and storage rooms can provide a buffer between these high-temperature rooms and the outside climate.

Appendix B: Overview of Selected Building Energy Performance Simulation Tools

There are currently many tools available for building energy analysis. One of the best overviews is the building energy software tools directory provided by the US Department of Energy (2002a). This directory now lists more than 200 tools, ranging from software that is still under development to commercial software. The directory is organized in the following main categories: whole-building analysis, codes and standards, materials, components, equipment and systems, and other applications.

A discussion of all 200 tools is not relevant for this thesis. Only a subset of those building energy tools that are suited for evaluation the performance of whole buildings is presented here. The tools that make up this subset are the most frequently used thermal simulation tools in current building energy simulation efforts and will be used throughout this thesis as examples. The tools are presented in alphabetical order.

- BDA (Lawrence Berkeley National Laboratory, 2002a)
  The Building Design Advisor is an environment that links several software modules that are relevant for building performance analysis and building design. Examples of such modules are a daylighting computation module, an electric lighting module, the DOE-2 simulation engine, a building browser (allowing to quickly describe and modify the objects and parameters that represent a building design), a decision desktop (allowing to compare performance predictions for different performance aspects and different design options), a schematic graphic editor, a default value selector (which automatically assigns values to parameters needed for simulation runs, but not specified by the user) and databases to store information. The BDA is intended for use by architects and engineers in early design phases. However, the tool does not seem to have had much impact on building practice yet. The BDA is under development by the Lawrence Berkeley National Laboratory, USA.

- Capsol (Physibel, 2002)
  Capsol is a commercial multi-zone transient heat transfer simulation program for the evaluation of heating, cooling, overheating, sunscreens and passive solar energy. Capsol adheres strictly to physical principles and hence is very useful for gaining insight. Through a series of input modules Capsol allows users to develop adequate building models without requiring programming skills. Capsol is made by Physibel, Belgium.

- EnergyPlus (US Department of Energy, 2002b)
  EnergyPlus is one of the few recently developed major building simulation tools. The development of this simulation engine is based on earlier experience with two well-known predecessors, BLAST and DOE-2. The development of EnergyPlus started in 1996; a first version was officially released in 2001.
  EnergyPlus currently includes heating, cooling, lighting, ventilating and other energy flows. Planned additional capabilities include multizone air flow and electric power simulation. The program is based on a new, modular structure and new computer code, in which the best capabilities of BLAST and DOE-2 have been adopted. EnergyPlus is developed by a team of specialists headed by the U.S. Department of Energy.

- Energy-10 (Lawrence Berkeley National Laboratory, 2002b)
  Energy-10 is intended as a design tool for architects and HVAC engineers. The tool is limited to commercial and residential buildings that are less than 10,000 ft^2 floor area. Development of a first building model to start evaluation and design is highly automated and can be based on four input values only; default values can be used for the rest of the building model. The program suggest energy-efficient building design alternatives and rank-orders simulation results. However, the underlying computational procedure is unclear. Apart from modifying default values to actual values there is not much influence on the building model, and most output values are fixed. Energy-10 only considers and optimizes for energy use and closely related aspects. The tool is developed by the Passive Solar Industries Council, USA.

- ESP-r (Energy Systems Research Unit, 2002)
  ESP-r is a dynamic thermal simulation program for the analysis of energy and mass flow problems within the built environment. ESP stands for Environmental System Performance, while the -r emphasizes research. The ESP-r system has seen continuous development since 1974. At the moment ESP-r consists of a central Project Manager which links together support databases, various simulation tools (energy, daylighting, CFD, complex control system simulation) and third party applications like CAD.
  ESP-r is developed and distributed by the Energy Systems Research Unit, University of Strathclyde, UK. ESRU offers dedicated courses for learning to work with the ESP-r system.

- IDA (Equa, 2002)
  IDA is a general purpose simulation environment geared towards the modeling and simulation of modular systems. IDA is designed for easy use, reuse and maintenance of the software tool. Models in IDA are described in NMF (Neutral Model Format), which is a program independent modeling language.
  An IDA version dedicated to the simulation of thermal comfort, indoor air quality and energy consumption named IDA-ICE (Indoor Climate and Energy) is commercially available; this version is mainly used by HVAC-designers and consultants, but also for other purposes like education and building research. IDA-ICE is developed by the Equa Simulation Technology Group (formerly known as Bris Data) in Sweden.

- Matlab/Simulink (MathWorks, 2002)
  Matlab is a general computing and analysis environment used by engineers worldwide, in all kinds of domains. Matlab includes mathematical, statistical and engineering functions. Simulink is a general simulation environment based on Matlab. Simulink allows modeling, simulation and analysis of dynamic systems, including buildings. The general applicability of Matlab and Simulink is advantageous through maintenance, testing and support. Matlab and Simulink are products of the MathWorks, USA.

- TRNSYS (Solar Energy Laboratory, 2002)
  TRNSYS is one of the most well-known thermal simulation tools. It is based on a modular approach. The program allows modeling of buildings and building systems using components from a standard library, but users can also define and use new components. TRNSYS is mainly used for HVAC analysis, building thermal performance prediction,

and study of control schemes. Tools for modeling systems independently from the TRNSYS tool itself are available in the form of PRESIM and IISiBat.

TRNSYS was introduced commercially as early as 1975; due to its modular lay-out it was possible to maintain the program. Currently TRNSYS version 15 is available; version 16 is expected to be released in May 2004. TRNSYS is developed by the Solar Energy Laboratory at the University of Wisconsin, USA. It is supported by distributors in the US, France, Germany, Belgium and Sweden. TRNSYS stands for transient system simulation program.

- VA114 (VABI, 1993)

  VA114 is a simulation tool that is widely used in the Netherlands. VA114 comes in different versions. The original version of VA114 was mainly intended to assess thermal behavior of office buildings, focusing on the typical lay-out of a corridor with office cells on each side, but VA114 now has been developed into a full dynamic model for the calculation of temperatures, overheating risk assessment, comfort calculation and heating and cooling requirements in rooms. The latest version also allows to import data from CAD programs etc.

  VA114 is under ongoing development by TNO Building and Construction Research in the Netherlands. The tool is distributed through VABI.

Appendix C: Process Descriptions and IDEF-0 Process Models of the Cases

Description of the design process of the Rijnland Office, Leiden

- General remarks
  The communication pattern between the parties involved ranged from intensive to incidental. The principal, architect and consultant for HVAC-systems met at least every two weeks; however, other participants had only one task and provided a report in writing. The architect was selected by means of a design competition, which took place during the phases of feasibility study and conceptual design. In the phase of final design the design team applied for the status of exemplary project in the field of energy-conscious and sustainable building; this status was granted during the next phase. As these two matters do not add essential information about the design process, they are not included in the process models.

- Feasibility study
  The architect started his work on the Rijnland Office in a systematical way. First he established the design goals, using the design brief provided by the principal. Next was the development of a strategy that would allow to meet these goals. The strategy contained the first ideas about a possible building layout (a ‘design in words’). Based on these ideas and some reference projects the architect could estimate the effort needed to realize his plans; thereupon he could assess the organizational, financial, technical and functional feasibility of the ideas.

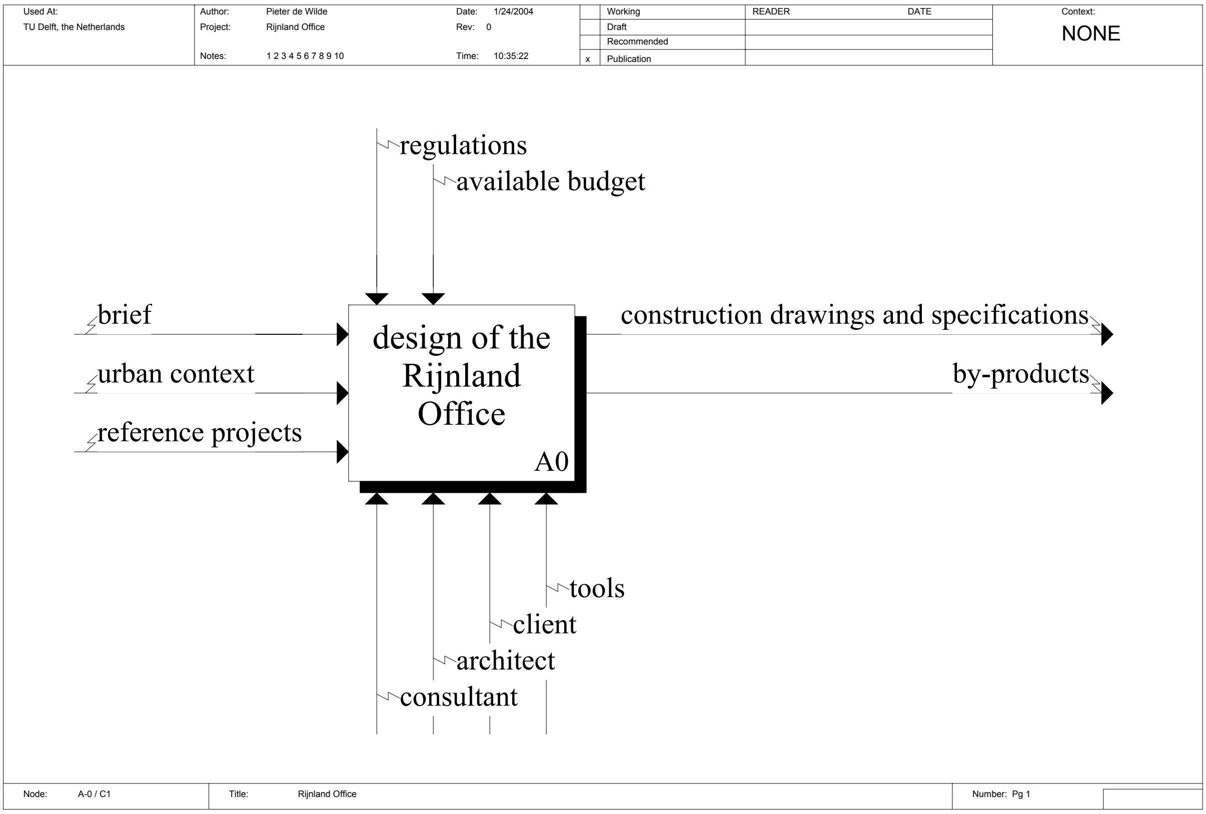
- Conceptual design
  The phase of conceptual design started very divergent but converged to the end. Starting point was a profound analysis of the brief and urban context of the building site. This lead to the formulation of the following four sub-goals: development of a specific image and building form, compliance with the functional program, connection to the urban context, and development of an environmentally-friendly building. With respect to this last sub-goal the architect himself decided to design an energy-efficient building; for support he contacted a consultant. Note that the formulation of the four sub-goals was an elaboration and rewriting of the original brief.
  The design process continued with the development of basic solutions for the sub-goals. This resulted in sketches of the building mass, an urban plan, and a functional arrangement/zoning plan. As far as energy efficiency was concerned the architect discussed the selection of energy saving building components with the consultant. Together they decided to use an aquifer (long term energy storage in the soil), heat pumps, low temperature heating, high temperature cooling, heat exchangers, a climate façade, daylighting systems and an atrium. According to the consultant these components, with the exception of the atrium, were quite independent from the architectural plan. This allowed the design team to detach the aspect of energy efficiency from the overall design process. The selection of these energy saving building components was mainly based on the input of the consultant who had used the same components in earlier projects.
  Finally all ingredients were combined into one conceptual design, which was presented to the principal. With the winning of the competition this design was accepted by the principal.

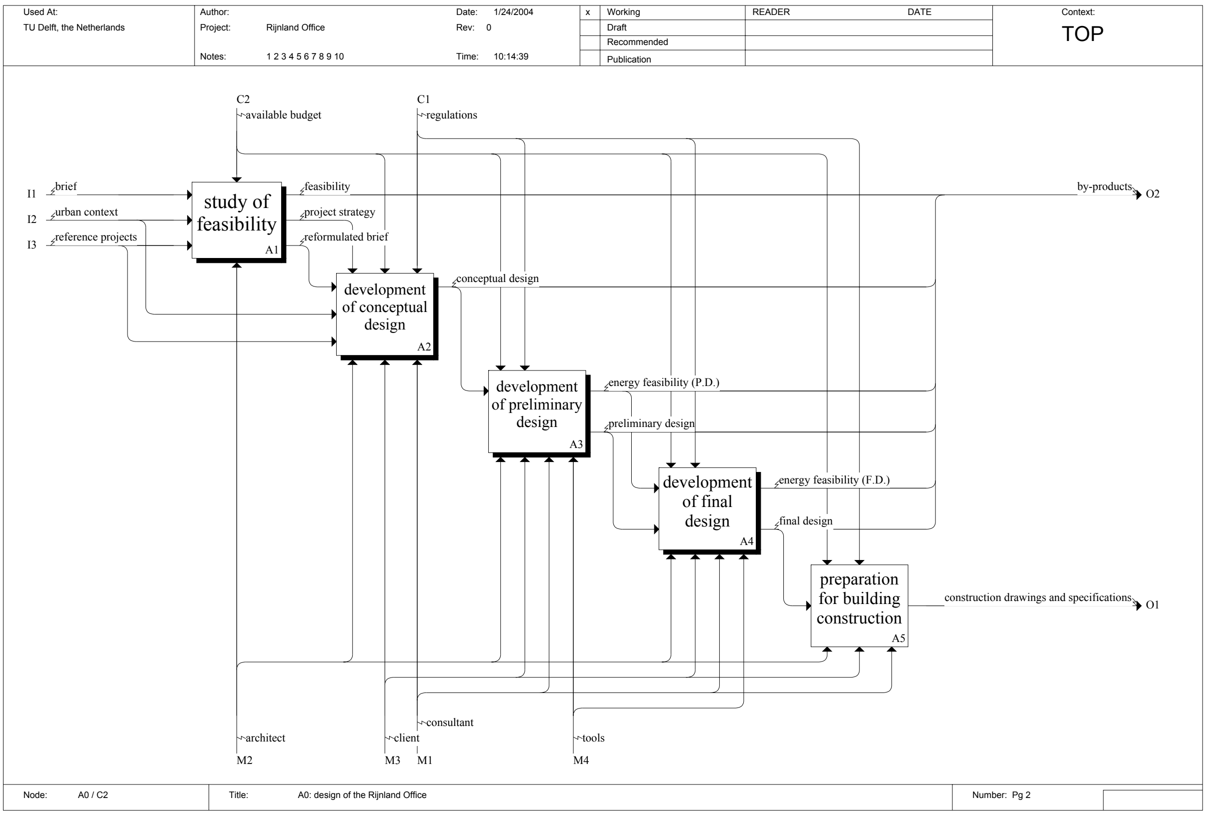
- Preliminary design
  During the phase of preliminary design the existing plans were further elaborated. Once again the architect took a systematic approach. He studied climate aspects, constructional aspects, the building site and installations. The results of these studies were combined into a draft of the preliminary design. This draft was checked for feasibility of the underlying concept, technical and financial feasibility, functional feasibility, and for energy aspects. After these checks the final version of the preliminary design was submitted to the principal for approval.
  For the energy aspects the consultants for installations made a substantial computational effort. He calculated the EP-coefficient, which is mandatory in Dutch building regulations. The consultant also performed dynamic energy simulation using the VABI VA114 program. In this simulation the aquifer and related long term energy storage in the soil were simulated using a separate tool named PIA-15; VA114 and PIA-15 were linked using a spreadsheet. Aim of these simulations was to confirm earlier assumptions as well as fine-tuning of systems that already were an integrated part of the building design concept.
  It is interesting to notice the following: the consultant contended that his evaluations provided feedback to all aspect studies and the subsequent integration, while the architect contended that the whole process was sequential, and that feedback would have be a major asset but was not received.

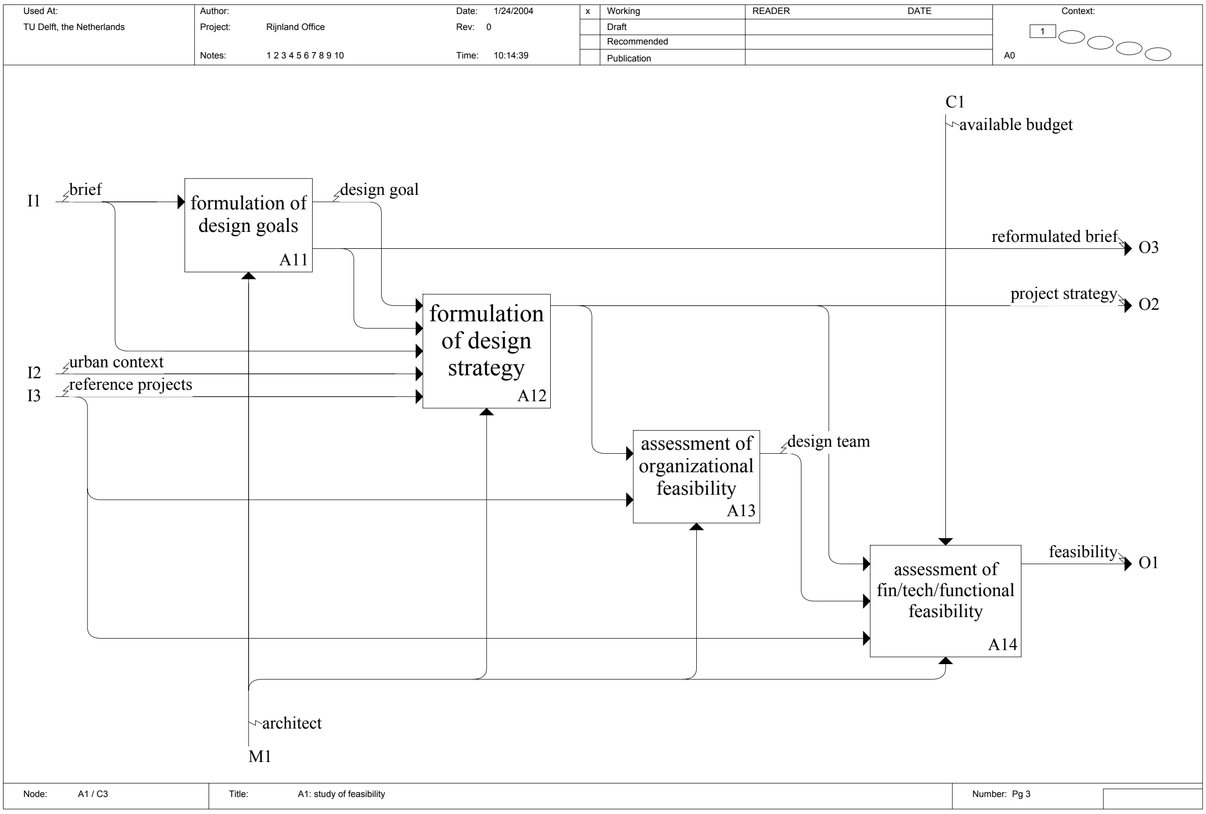
- Final design
  The phase of final design was similar to the phase of preliminary design. Again, the existing plans were detailed; however this time the starting point was the preliminary design. The architect studied constructional aspects, HVAC-systems and the building façade. The results were combined into a draft version of the final design. This draft was checked for the same aspects as the draft of the preliminary design: for feasibility of the underlying concept, technical and financial feasibility, functional feasibility, and for energy aspects. However, the content of these checks was different. For instance the check on energy aspects now followed the development of the façade by the architect and hence focused on the evaluation of daylighting systems. This work involved both lighting simulations and the use of an experimental set-up to assess reflective Venetian blinds and a reflective ceiling element. The consultant also recalculated the EP-coefficient in order to obtain the final value, which was needed for the building permit. The resulting final design was submitted to the principal for approval.

- Preparation of building specifications and construction drawings
  In this phase the design was detailed once more. Specific products were selected and tolerances were defined. At the end of this phase all parts of the building design were specified in construction drawings and a bill of quantities. However, al this work did hardly change the final building design as defined in the previous phases.

IDEF-0 process models representing the design of the Rijnland Office, Leiden



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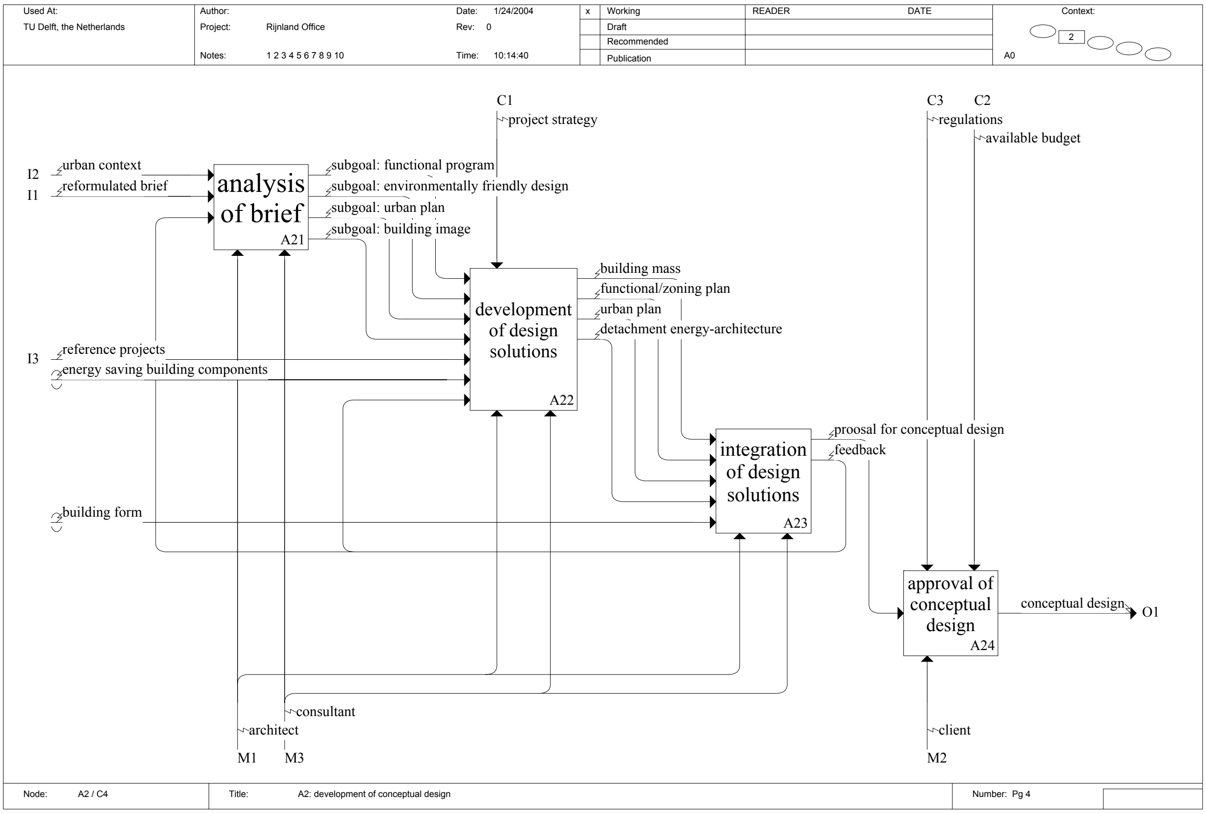
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C3
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urban context
I1
reformulated brief
analysis of brief
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subgoal: functional program
subgoal: environmentally friendly design
subgoal: urban plan
subgoal: building image
development of design solutions
A22
building mass
functional/zoning plan
urban plan
detachment energy-architecture
I3
reference projects
energy saving building components
integration of design solutions
A23
proosal for conceptual design
feedback
building form
approval of conceptual design
A24
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architect
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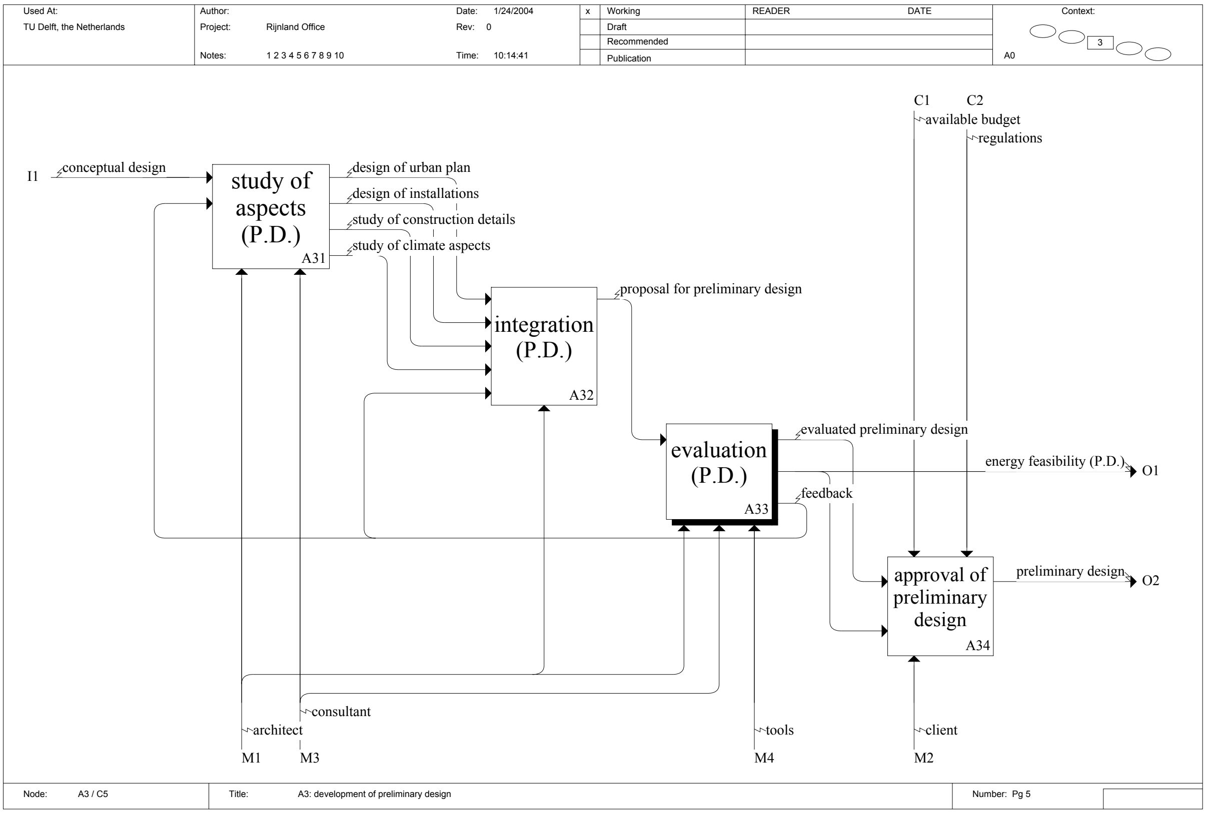
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A31
design of urban plan
design of installations
study of construction details
study of climate aspects
integration (P.D.)
A32
proposal for preliminary design
evaluation (P.D.)
A33
evaluated preliminary design
energy feasibility (P.D.)
O1
feedback
approval of preliminary design
A34
preliminary design
O2
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tools
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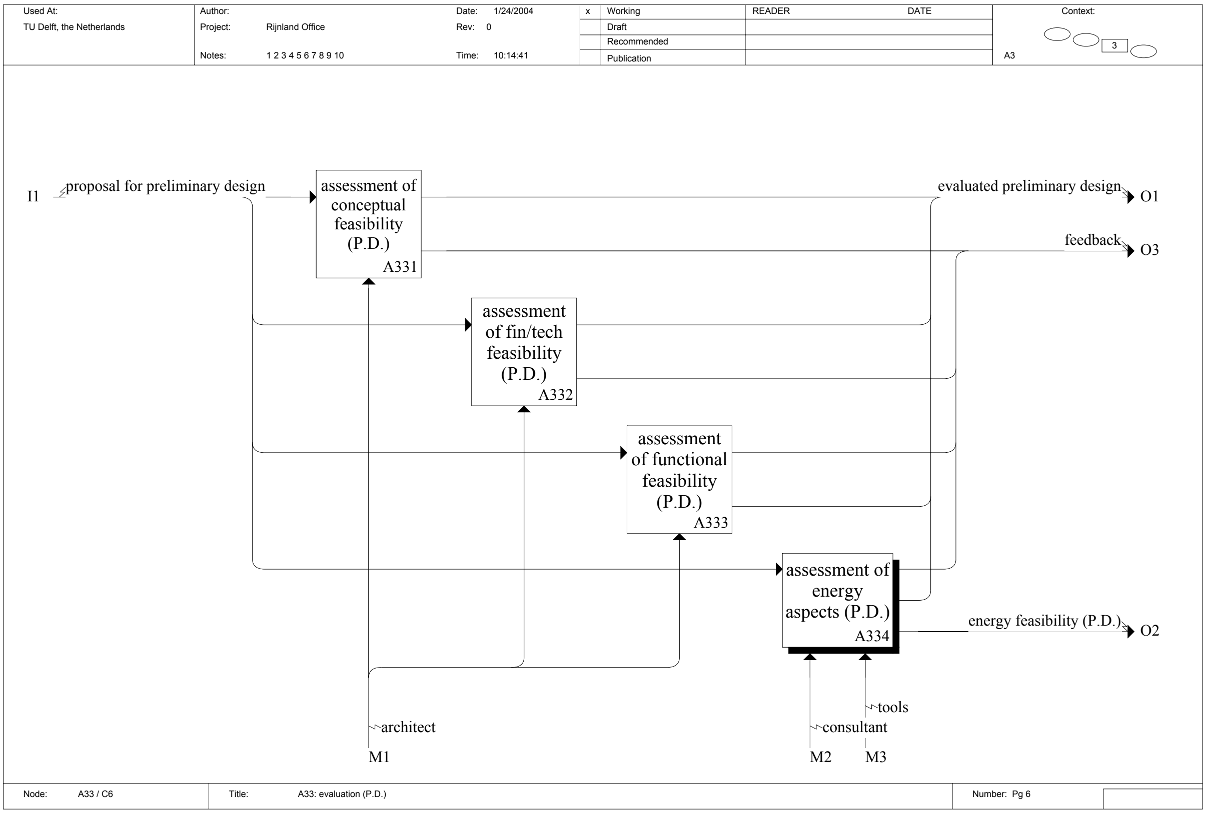
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O1
feedback
O3
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A332
assessment of functional feasibility (P.D.)
A333
assessment of energy aspects (P.D.)
A334
energy feasibility (P.D.)
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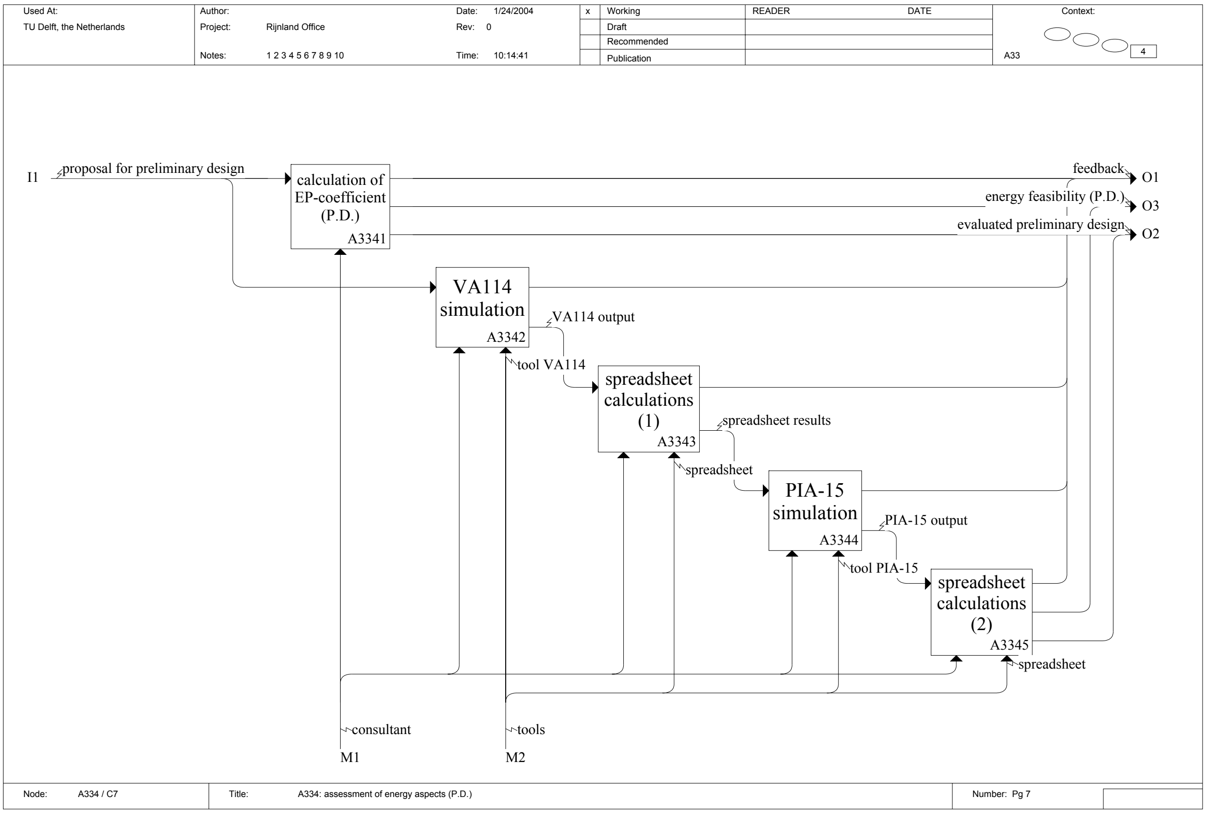
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VA114 output
tool VA114
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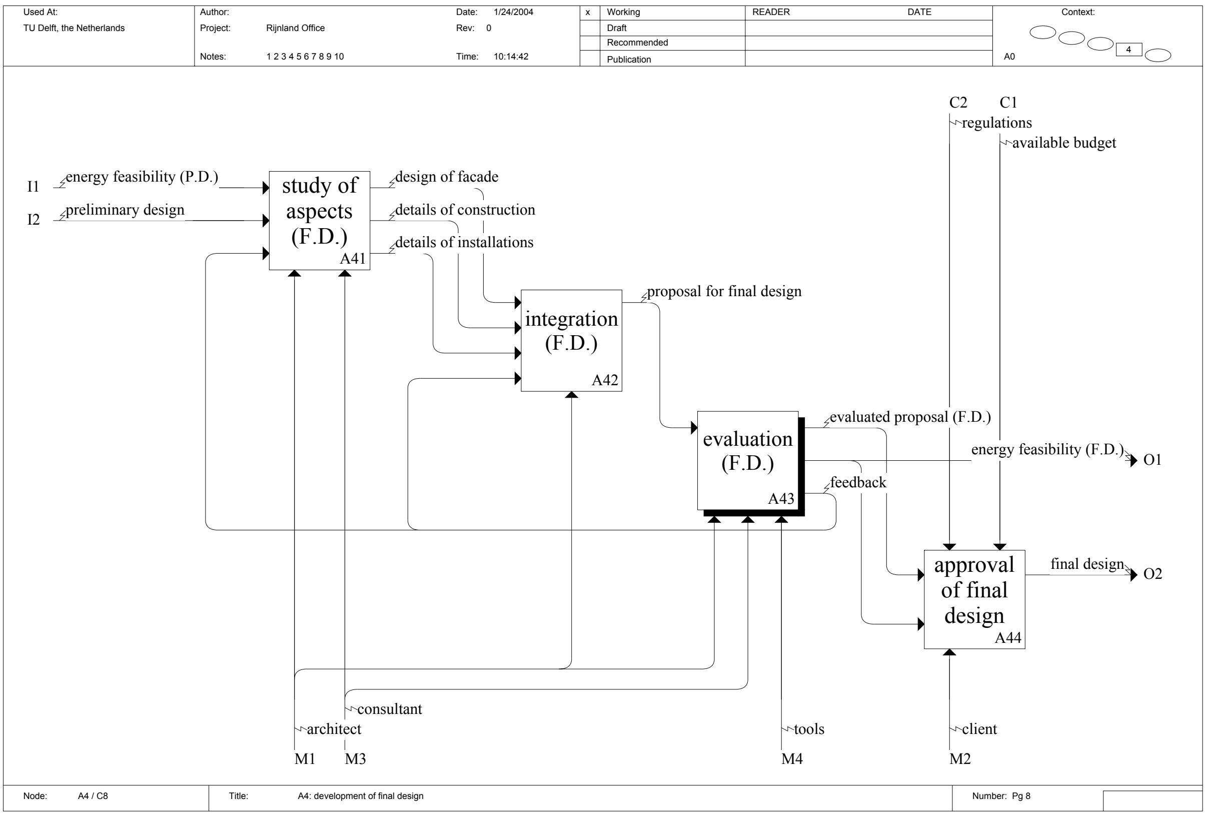
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design of facade
details of construction
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integration (F.D.)
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proposal for final design
evaluation (F.D.)
A43
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energy feasibility (F.D.)
O1
feedback
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final design
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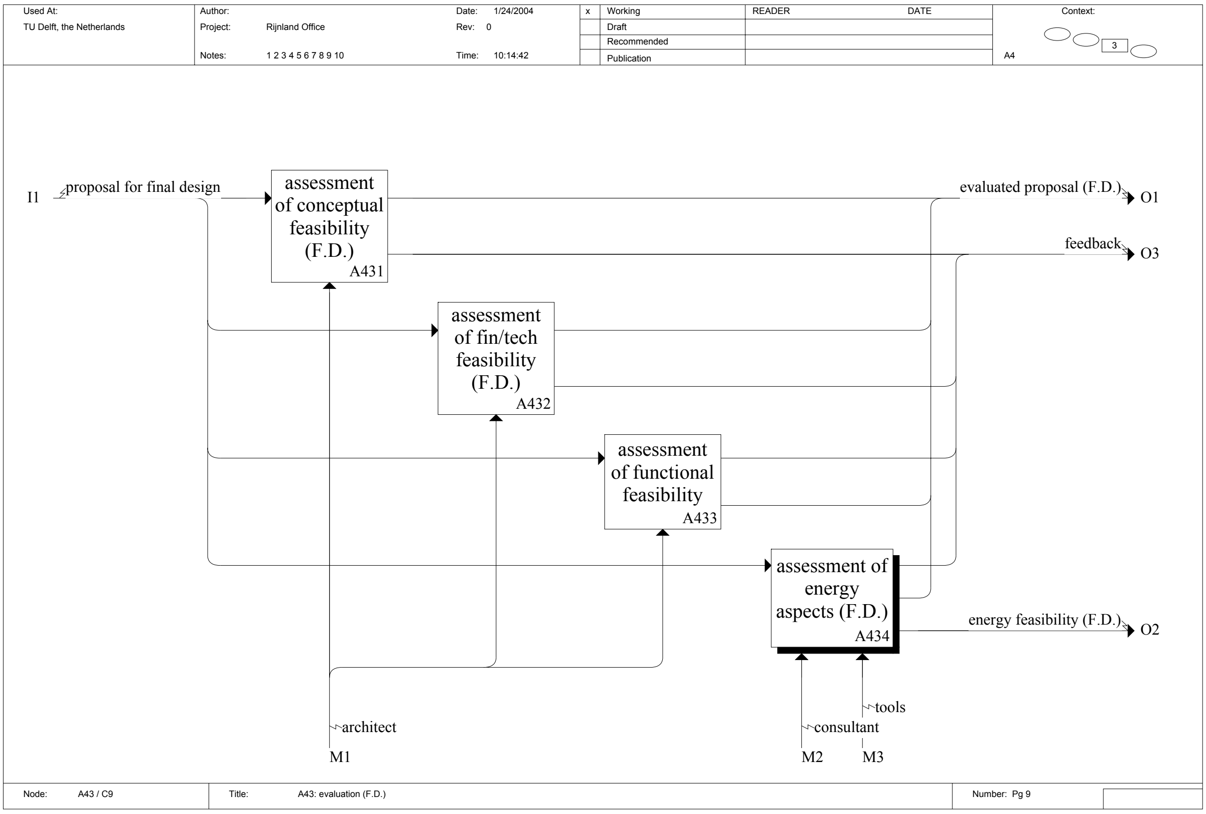
Number: Pg 8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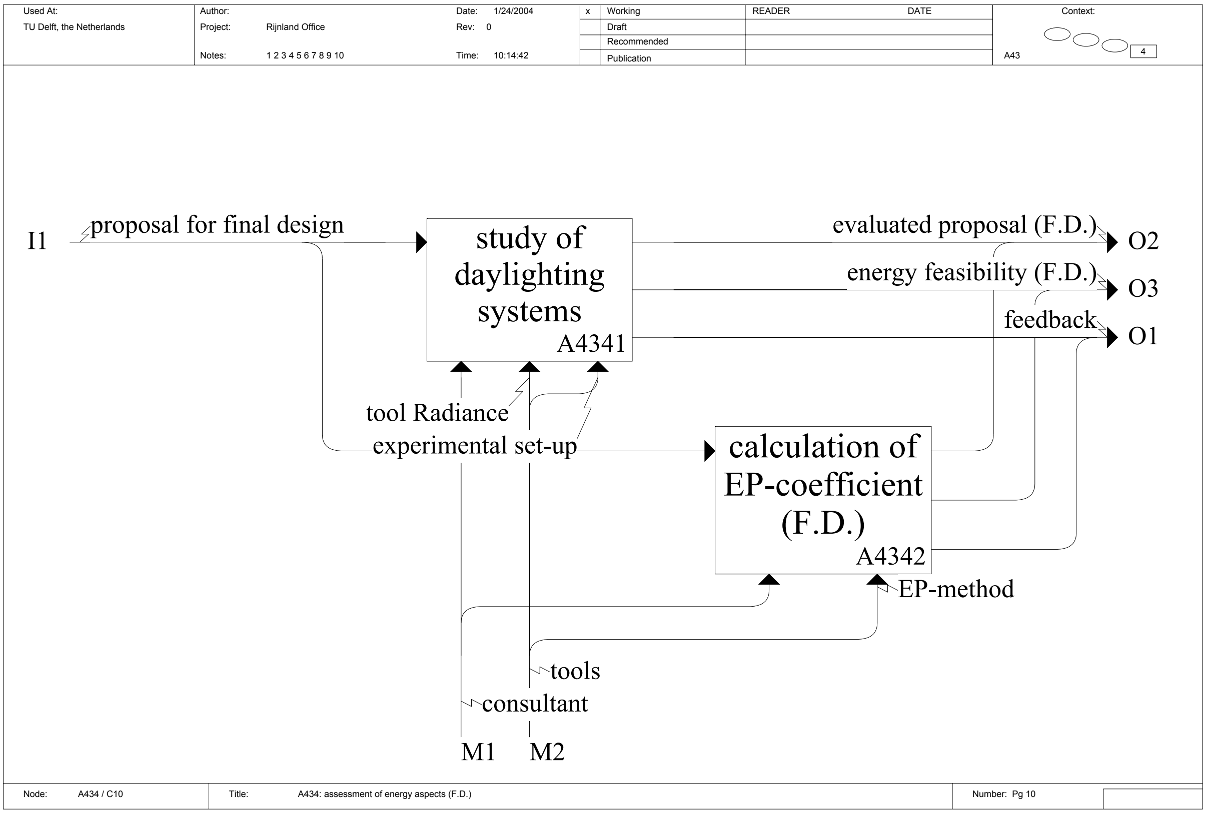
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EP-method
tools
consultant
M1
M2
Node: A434 / C10
Title: A434: assessment of energy aspects (F.D.)
Number: Pg 10

Description of the design process of ECN Building 42, Petten

- General remarks
  The project group of all participants working on the design of ECN Building 42 deliberated on a regular basis. Usually all actors actively involved in the process met every two weeks.
  A peculiarity of the design of ECN Building 42 was the fact that the design process initially was a fast track process: in practice the phases of feasibility study and conceptual design were combined into one stage. This is not reflected by the IDEF-0 process models in order to maintain maximal similarity between the three process models of the cases.
  Another characteristic was that the principal and consultant for renewable energy started their work on the project before they called in an architect. The related activities are described in an additional phase: preparation of the design request.

- Preparation of the design request
  The development of ECN Building 42 was initiated by a need for additional offices and laboratories. Due to the renovation of another building in use with ECN the new building was needed relatively soon, resulting in an implicit decision for a fast track design process.
  In this case the decision to employ an architect was not evident: in the past, all new buildings for ECN had been developed internally by ECN divisions. An analysis of these earlier projects resulted in an aspiration for more functional and more architectural appealing building design, and hence in the decision to call in an architect. The consultant for renewable energy was the moving spirit behind this departure from the normal course of events.
  As the building was to be designed for a research institute specializing in all energy-related issues, it is obvious that energy efficiency was a prominent aspect of the brief. This was reflected by the ambition to achieve an EP-coefficient of 0.9. As stated before the EP-coefficient is a mandatory energy performance indicator (ratio) used in Dutch building regulations. At that moment in time the Dutch building code required an EP-coefficient of 1.6 for office buildings.

- Feasibility study
  The architect started by studying the feasibility of the project. He examined all relevant constraints (building regulations, technical aspects, financial aspects), the intended user categories of the building, and the brief as formulated by the principal: requirements concerning the building site, financial requirements, and specific requirements concerning the design (flexibility, connection to other buildings, shading of other buildings (with photovoltaic arrays), required space and zoning, and facilities to be provided). The results of these studies were combined into an updated and extended brief.
  As the first stage of the design process was fast track there is a seamless transition between the feasibility study and the phase of conceptual design.

- Conceptual design
  For ECN Building 42 the phase of conceptual design consisted of three parts. First, a number of building design alternatives was developed; this development of building design alternatives followed the requirements. The building site was a major determinant: as the site is owned by the Dutch National Forestry Service, very strict regulations applied. These regulations dictated the coordinate system for the plan, and hence (solar) orientation. Some possible arrangements of building volume were developed. As there

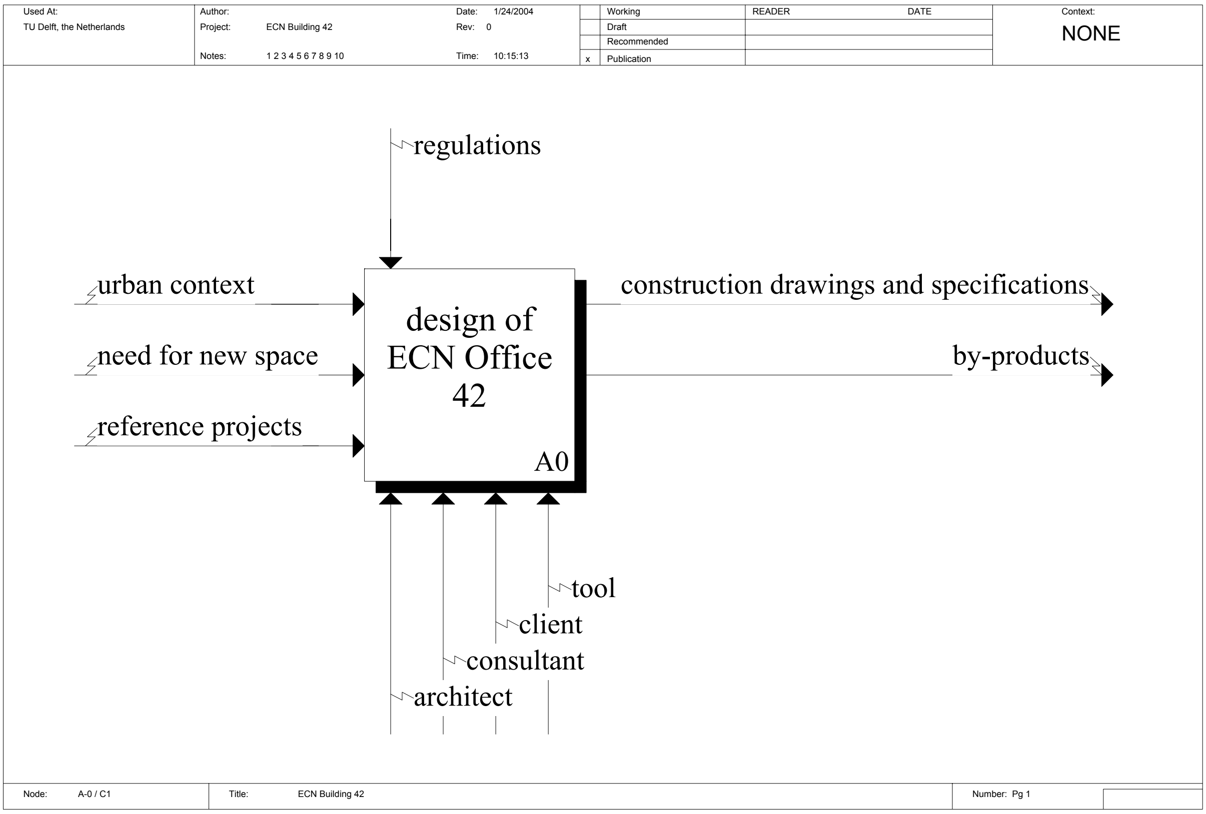
were few choices the building design quickly obtained its final form: three units connected by a central conservatory. Second, the architect selected energy saving building components and integrated these into the building design. First he considered heating and cooling; he decided to use an existing cogeneration unit, fixed shading devices for the conservatory, and nocturnal ventilation in summer. Next he considered ventilation; he decided to make maximal use of natural ventilation and to use heat exchangers for all mechanical ventilation. Then he considered lighting; for daylighting the office rooms atria were introduced into each of the building units. Finally he considered use of renewable energy; this resulted in the selection of photovoltaic arrays which also play a role as fixed shading devices for the conservatory. All energy saving components were selected to fit into the building design, so integration into a final design was simple. However, there was no evaluation of the interaction between components, or of optimal parameter values for the building design and energy saving building components. Third, the resulting drawing was presented to the principal for approval.

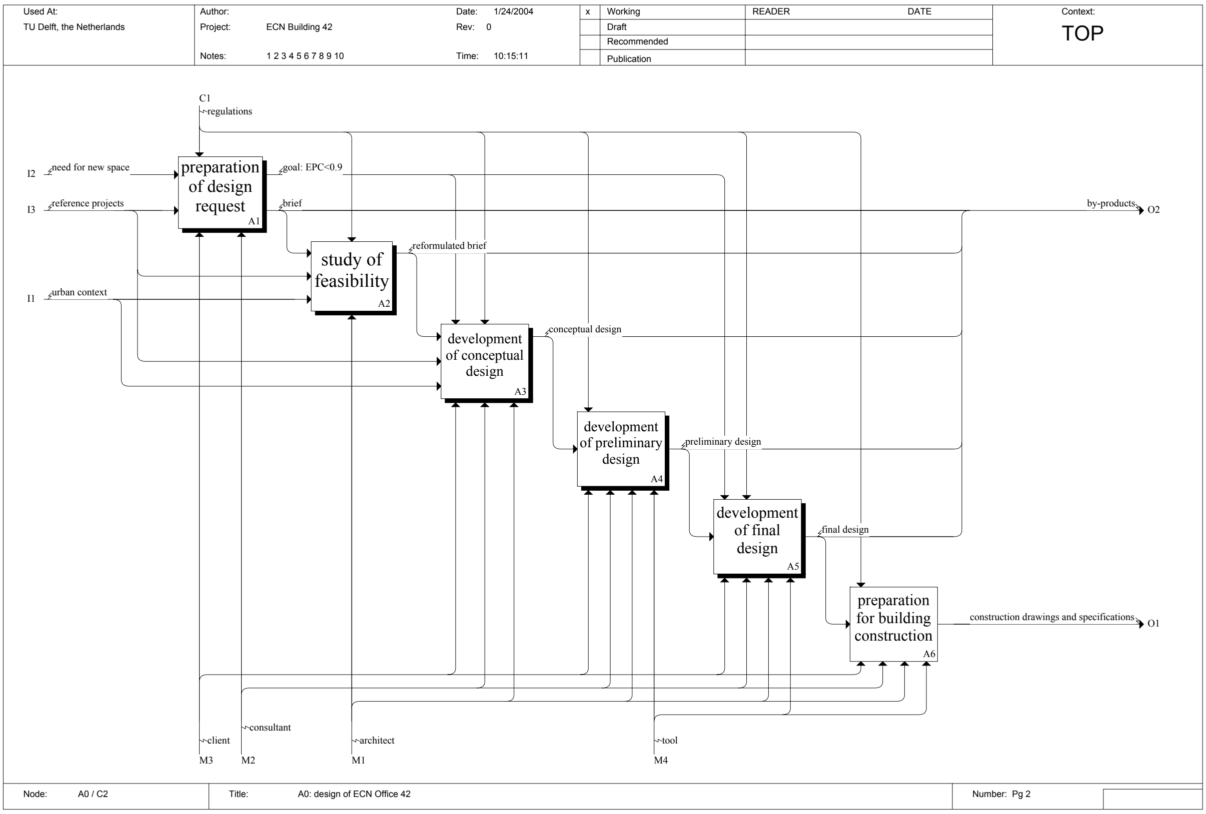
- Preliminary design
  During the phase of preliminary design the architect elaborated the conceptual design. The architect himself calculated the EP-coefficient to check whether or not his design met the value of 0.9 specified in the brief. The consultant for renewable energy calculated the EP-coefficient, too. However, this was for verification purposes only, doubling the calculations of the architect. The resulting preliminary design was presented to the principal for approval.

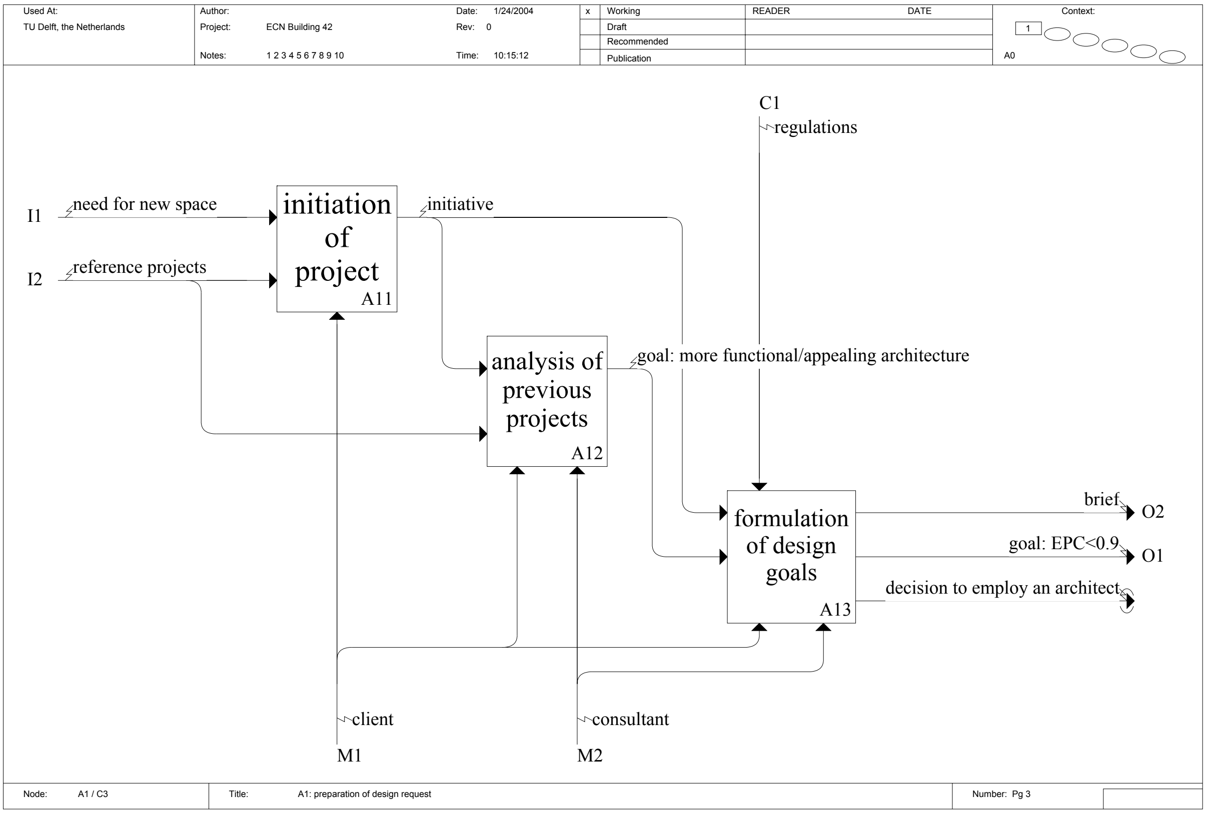
- Final design
  During the phase of final design the architect detailed the preliminary design. Simultaneously the consultant for HVAC-systems worked on these HVAC-system using a range of VABI-tools; the main result of this work were the dimensions of the HVAC-components. These data then were incorporated into the final design by the architect. The consultant for renewable energy verified the EP-coefficient once again. Furthermore, he made a dynamic simulation using TRNSYS to assess the risk of overheating. The resulting final design was presented to the principal for approval.

- Preparation of building specifications and construction drawings
  Finally the design was completed with the development of construction drawings and building specifications. However, no more changes to the basic building design were made.

IDEF-0 process models representing the design of ECN Building 42, Petten



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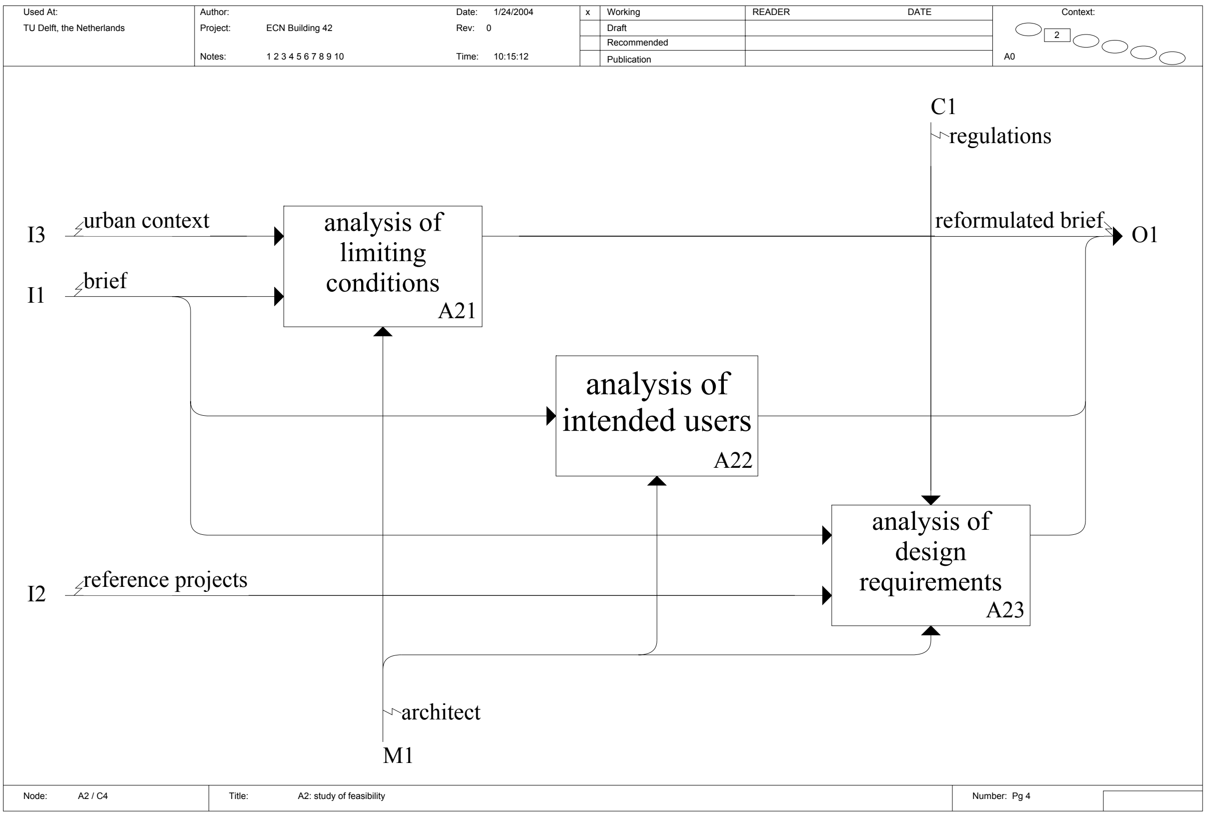
READER
DATE
Context:
A0
C1
regulations
I1
need for new space
I2
reference projects
initiation of project
A11
initiative
analysis of previous projects
A12
goal: more functional/appealing architecture
formulation of design goals
A13
brief
O2
goal: EPC<0.9
O1
decision to employ an architect
client
M1
consultant
M2
Node: A1 / C3
Title: A1: preparation of design request
Number: Pg 3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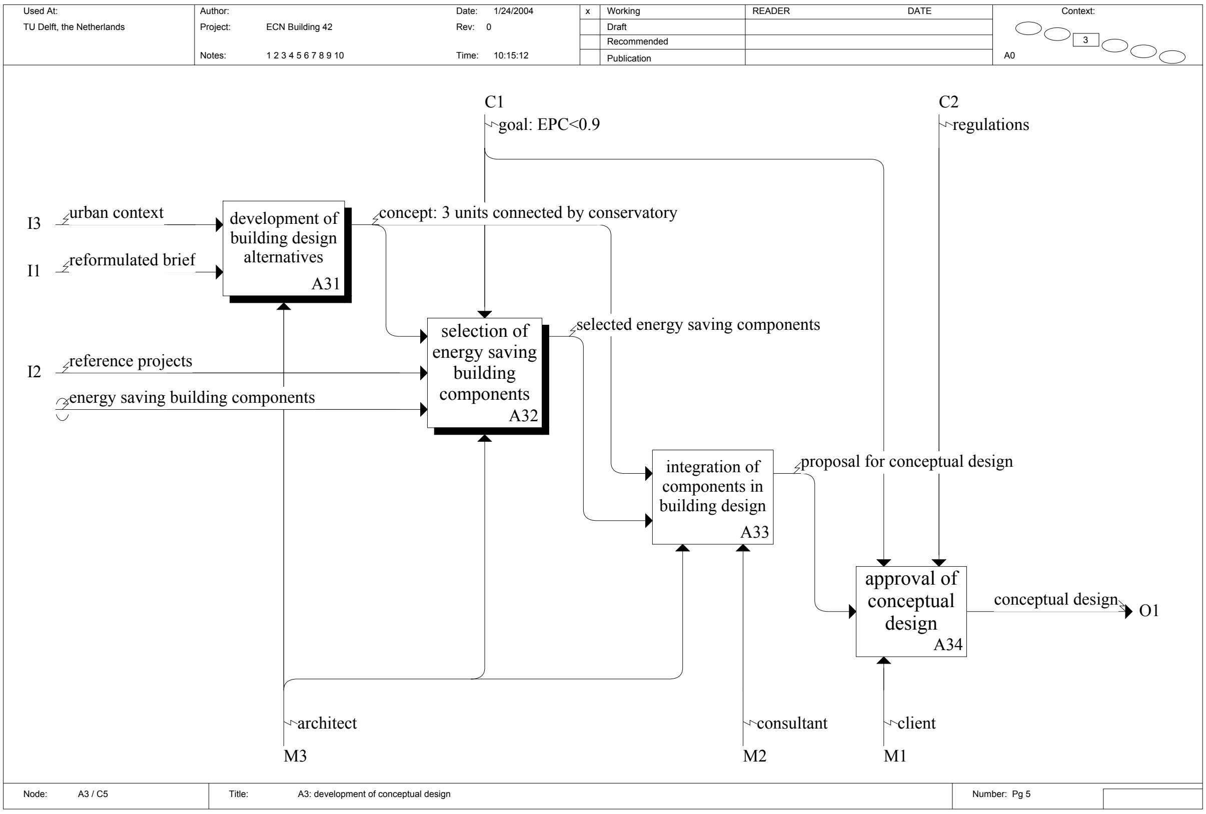
DATE
Context:
A0
C1
regulations
I3
urban context
I1
brief
analysis of limiting conditions
A21
reformulated brief
O1
analysis of intended users
A22
analysis of design requirements
A23
I2
reference projects
architect
M1
Node: A2 / C4
Title: A2: study of feasibility
Number: Pg 4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Publication
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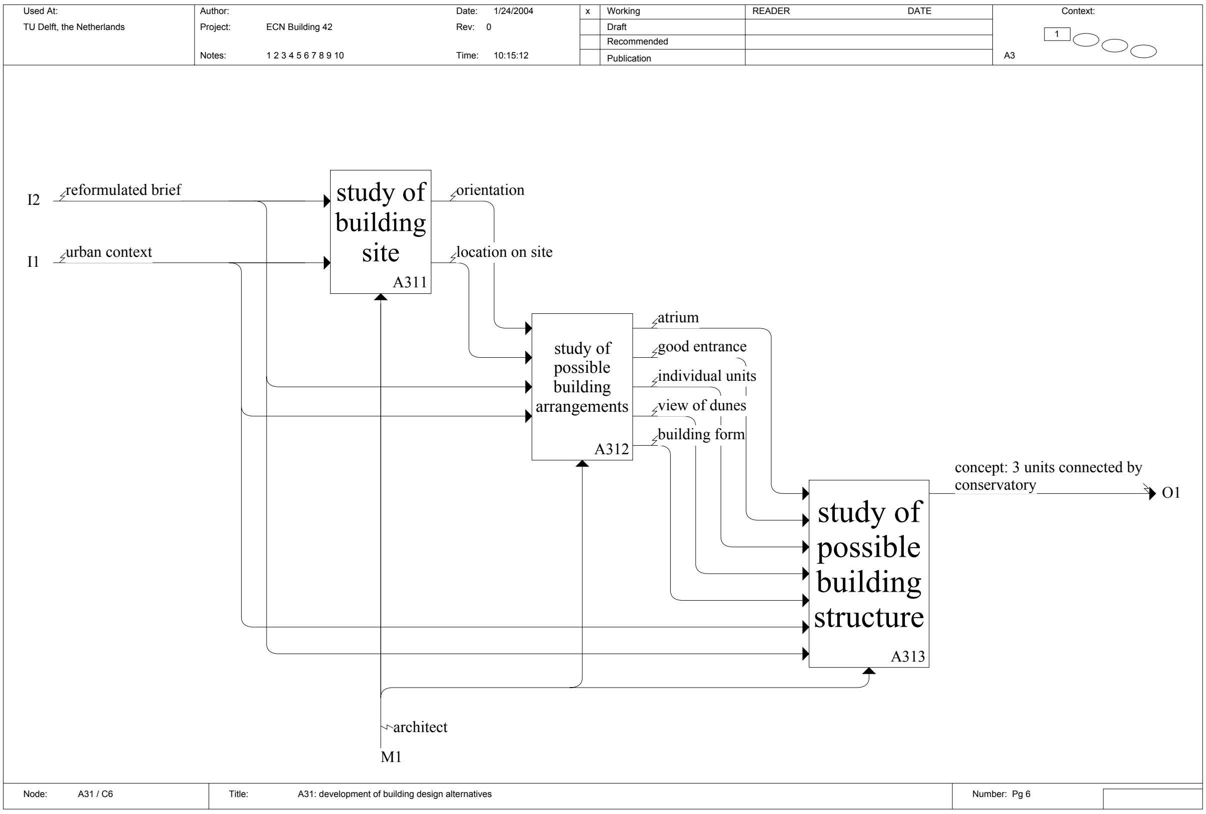
DATE
Context:
3
A0
C1
goal: EPC<0.9
C2
regulations
I3
urban context
I1
reformulated brief
development of building design alternatives
A31
concept: 3 units connected by conservatory
selection of energy saving building components
A32
selected energy saving components
I2
reference projects
energy saving building components
integration of components in building design
A33
proposal for conceptual design
approval of conceptual design
A34
conceptual design
O1
architect
M3
consultant
M2
client
M1
Node: A3 / C5
Title: A3: development of conceptual design
Number: Pg 5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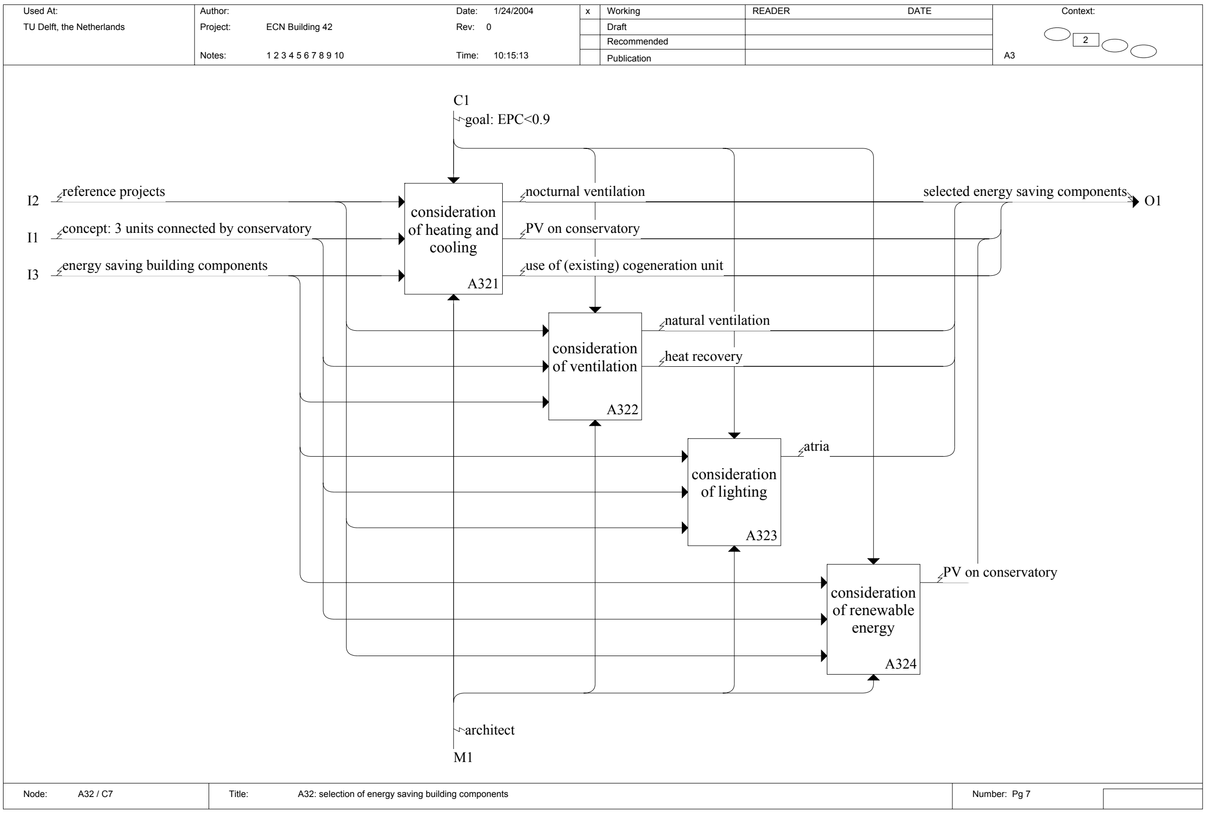
Draft
Recommended
Publication
READER
DATE
Context:
1
A3
I2
reformulated brief
I1
urban context
study of building site
A311
orientation
location on site
study of possible building arrangements
A312
atrium
good entrance
individual units
view of dunes
building form
study of possible building structure
A313
concept: 3 units connected by conservatory
O1
architect
M1
Node: A31 / C6
Title: A31: development of building design alternatives
Number: Pg 6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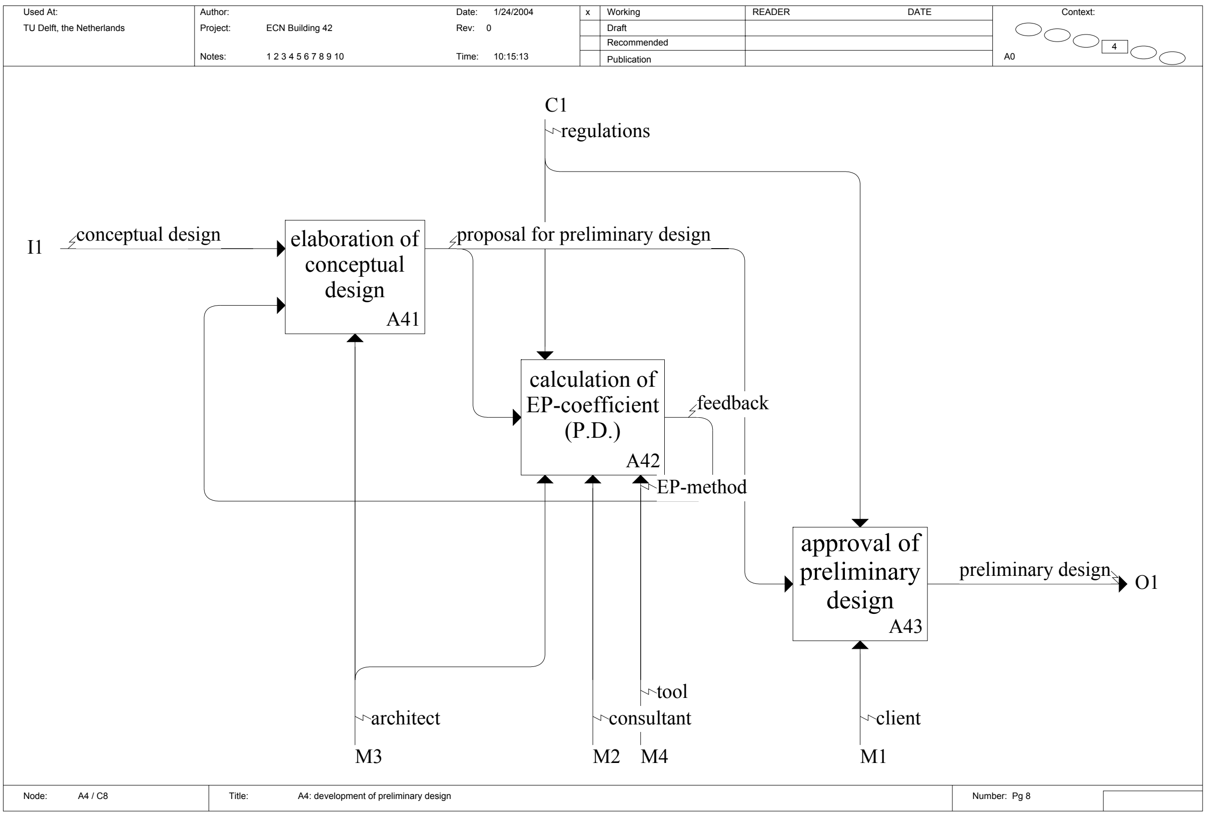
Draft
Recommended
Publication
READER
DATE
Context:
A3
C1
goal: EPC<0.9
I2 reference projects
I1 concept: 3 units connected by conservatory
I3 energy saving building components
consideration of heating and cooling
A321
nocturnal ventilation
PV on conservatory
use of (existing) cogeneration unit
selected energy saving components
O1
consideration of ventilation
A322
natural ventilation
heat recovery
consideration of lighting
A323
atria
consideration of renewable energy
A324
PV on conservatory
architect
M1
Node: A32 / C7
Title: A32: selection of energy saving building components
Number: Pg 7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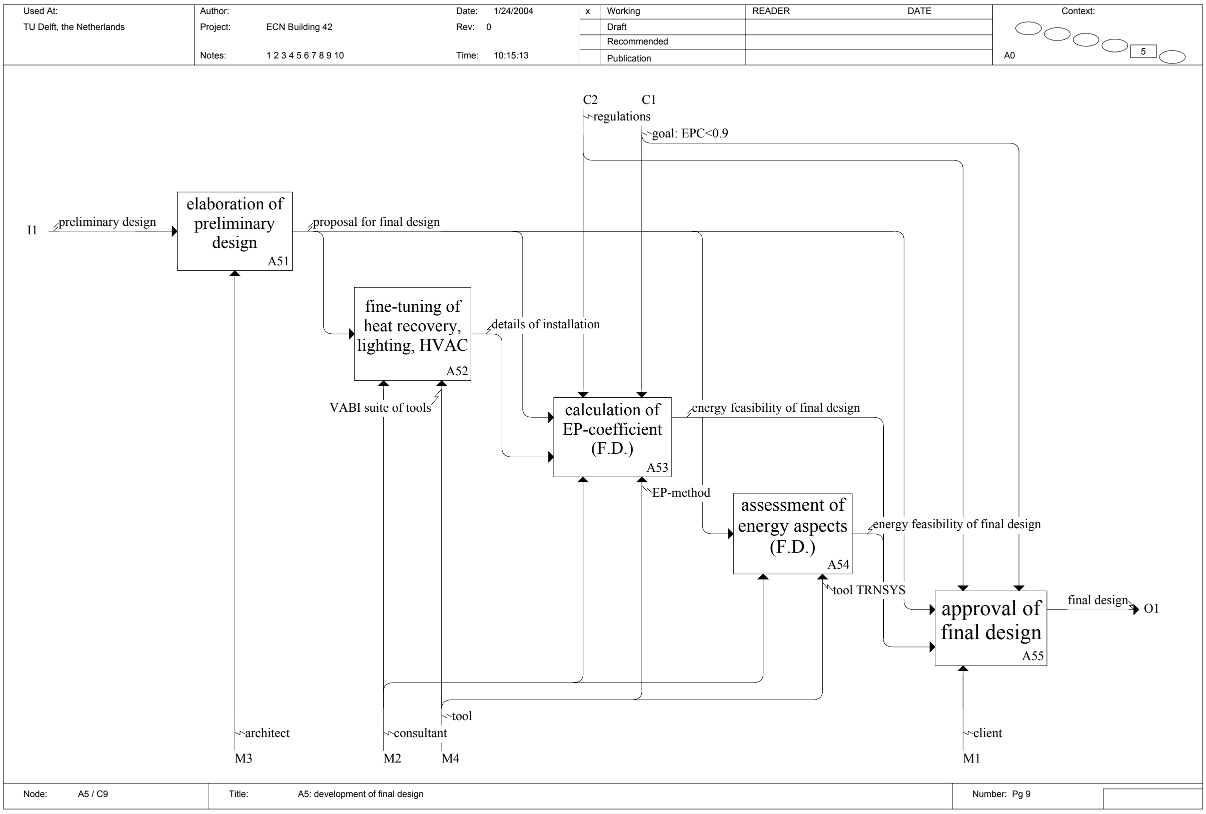
DATE
Context:
A0
C1
regulations
I1 conceptual design
elaboration of conceptual design
A41
proposal for preliminary design
calculation of EP-coefficient (P.D.)
A42
feedback
EP-method
approval of preliminary design
A43
preliminary design
O1
architect
M3
tool
consultant
M2 M4
client
M1
Node: A4 / C8
Title: A4: development of preliminary design
Number: Pg 8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DATE
Context:
A0
5
C2
C1
regulations
goal: EPC<0.9
I1
preliminary design
elaboration of preliminary design
A51
proposal for final design
fine-tuning of heat recovery, lighting, HVAC
A52
details of installation
VABI suite of tools
calculation of EP-coefficient (F.D.)
A53
energy feasibility of final design
EP-method
assessment of energy aspects (F.D.)
A54
energy feasibility of final design
tool TRNSYS
approval of final design
A55
final design
O1
tool
architect
consultant
client
M3
M2
M4
M1
Node: A5 / C9
Title: A5: development of final design
Number: Pg 9

Description of the design process of the Dynamic Office, Haarlem

- General remarks
  The design process of the Dynamic Office as well as the resulting building are dominated by the complex building site next to the Haarlem railway station. The here described process was the second attempt to develop a building design for this site, since an earlier attempt by another architect had failed. As the earlier project influenced the design of the Dynamic Office, this earlier design work is included in the process model. The building responds in different ways to the context, as will be described in the text about the design process.
  In this project the architect had to deal with two principals: the official principal as well as the main tenant. The tenant was the Government Buildings Agency. Accordingly, it had quite some influence on the design. Most energy-efficient aspects of the Dynamic Office were introduced by the consultant to meet the demands of the Government Buildings Agency.

- Preceding design process
  The design process of the Dynamic Office was preceded by another design process by another architect. The resulting design was rejected by the architectural advisory services, and subsequently was abandoned by the principal. However, this previous design process resulted in an important starting point for the design of the Dynamic Office: it proved that a normal office building was not feasible on this building site. Hence the design process of the Dynamic Office aimed at a low and deep building.

- Feasibility study
  The very first activity of the architect was to study the feasibility of the development of a building design for this specific location. To do so, the architect studied the earlier design process and resulting building design. The next step was a profound study of the brief. In consultation with the tenant this brief was adjusted to reflect the most actual design goals. An important change in the brief concerned thermal comfort: the tenant required a maximum of 150 weighted degree hours as defined and computed by the VABI-tool VA114. This provided both a hard design requirement as well as a prescribed tool for performance assessment.

- Conceptual design
  The architect says to have an affinity for complex situations and likes to let these situations inspire his designs. Hence he started by dividing the overall building design goal in sub-goals (building site, program, building system, daylighting); he then tried to develop one integral solution. The building site (and the previous design process) resulted in a low and deep building. For building mass the architect decided to use a number of hidden office floors and a special top floor. He made a distinct front in the direction of the station square. The building program resulted in a further development of the lay-out of the plan; a traverse and office floors that rise to the end of the building were introduced. The building system provided building structure and building dimensions, and offered some points of departure for the development of the façade. As the building was to become low and deep the architect wanted to introduce daylight into the building; several possibilities were studied. His first idea was to make a lighting row. In order to allow better communication between the offices on both sides of this row the lighting row was transformed into a series of atria. Due to building image and building functions these atria

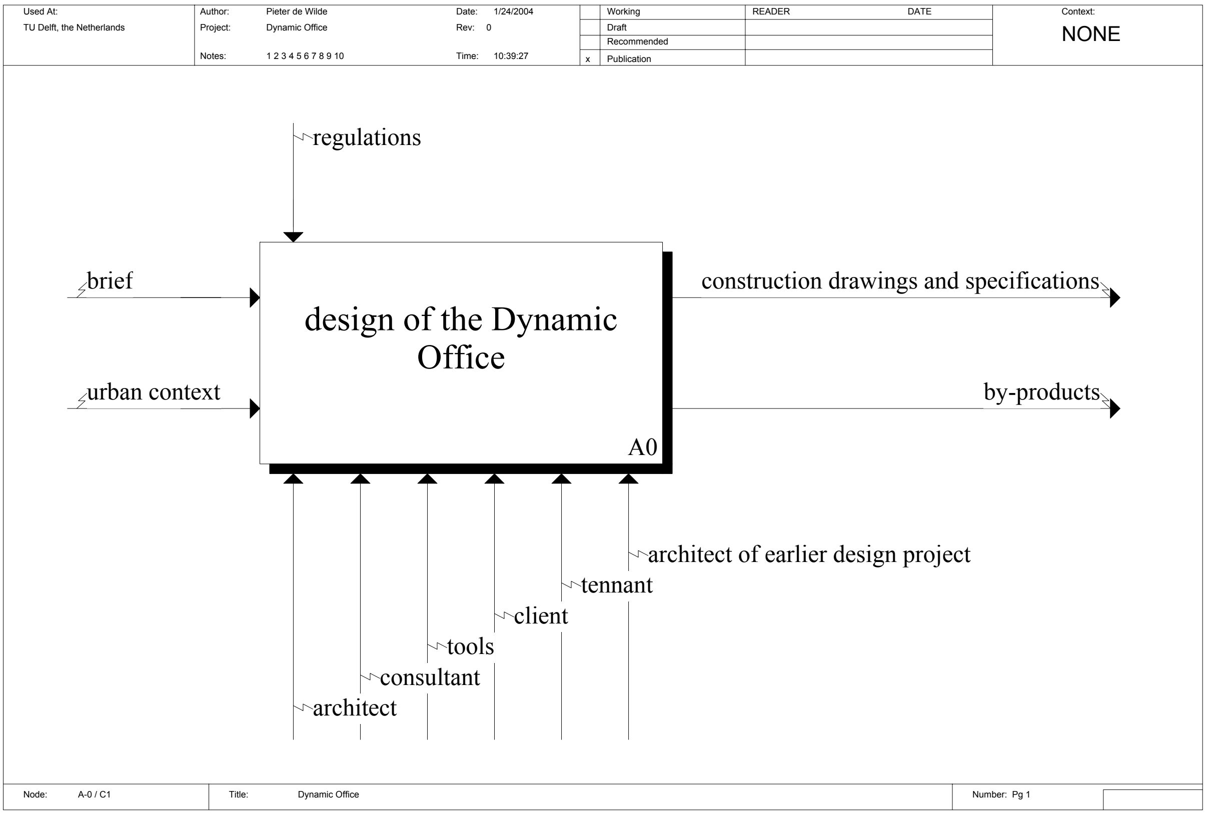
were then positioned in a staggered manner. Finally all ideas were presented in one conceptual building design, which was approved by the principals.
During the whole phase of conceptual design a consultant for HVAC-systems was part of the project team. This consultant provided feedback on general issues, but did not use any computational tools. Instead, he relied on experience and common sense.

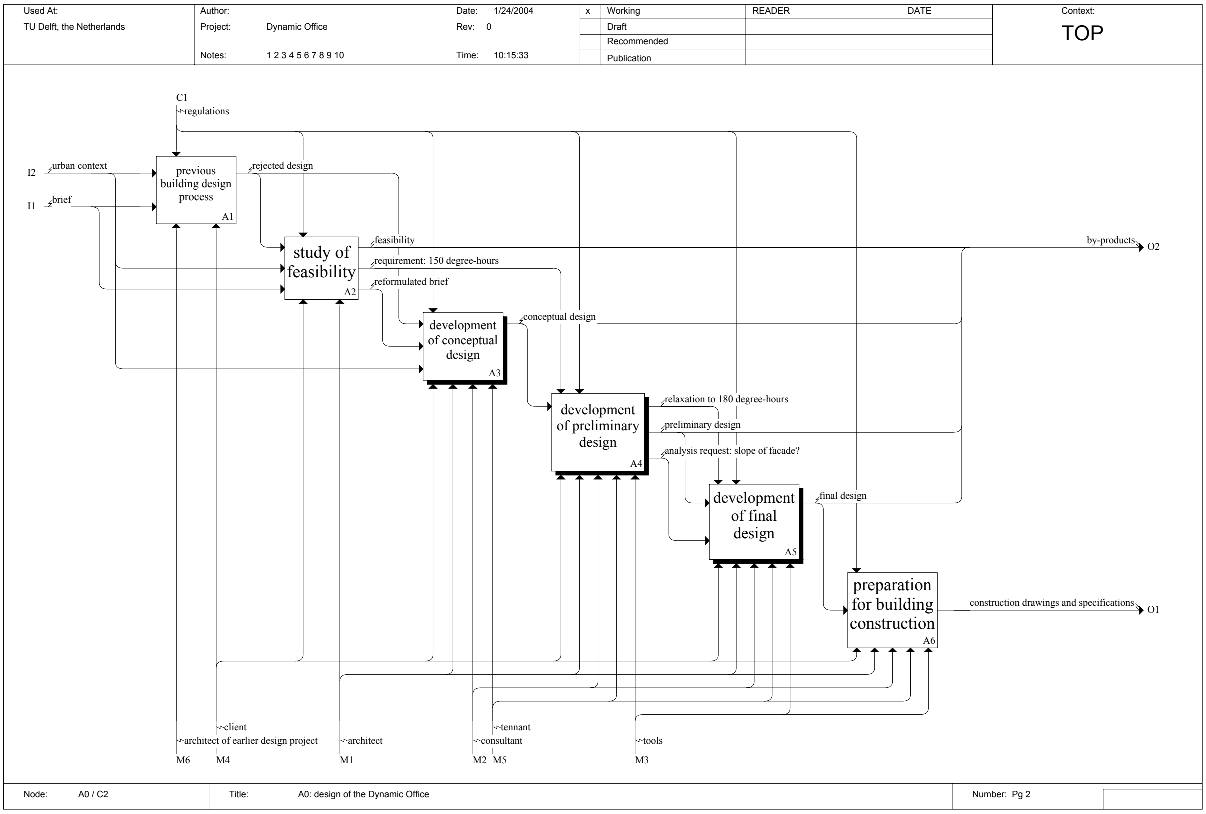
- Preliminary design
  During the phase of preliminary design the architect elaborated the conceptual design. An important part of this elaboration was the design of the façade, based on the starting points developed during the conceptual design.
  The consultant for HVAC-systems started working on the energy efficiency of the building. Keeping in mind the requirements of the tenant concerning thermal comfort he tried to achieve a building design in which a cooling plant would be superfluous. The consultant started by testing the conceptual design for compliance with the requirement of 150 weighted degree hours. Using the prescribed tool VA114 he performed a first test simulation. This test resulted in an exceeding of the 150 weighted degree hours. The consultants now verified the correctness of his physical model and input data. When was certain that his input was correct he analyzed the causes of the temperature curve and developed an approach to meet the requirements. He assessed solar gain, ventilation, internal heat sources and the use of thermal mass. As a result he informed the architect that the building would need mechanical ventilation, that it was important to minimize internal heat production, that the façade had to be heavy (thermal mass) and that external sunshading was needed. Moreover, the requirement of 150 weighted degree hours was relaxed to 180 hours after discussion with the tenant.
  The consultant's feedback provided important input for the development of the façade. The architect designed a concrete façade with three glazed areas: one area allowing seated people an unobstructed view, one area allowing standing people an unobstructed view, and one area allowing daylighting. Front beams in between these zones double as external sunshading.
  In order to balance solar access, daylighting and thermal comfort the architect decided to tilt the façade outwards. The consultant was to decide on the optimal angle. However, this angle has not been determined during the preliminary design.
  The preliminary design (including the design of the façade) was presented to, and approved by, the principal and the tenant.

- Final design
  During the phase of final design the architect detailed the preliminary design. Parallel to this work the consultant continued assessment of the building design. Results of his work were integrated into the draft of the final design. In this phase the consultant assessed the thermal comfort in the atria (resulting in a 'hood' on the atria and controllable ventilating grids), determined the angle of the façade (resulting in a shading angle of 50^{o}) and assessed further use of available thermal mass (resulting in partially open ceilings). By application of energy-efficient computers and efficient artificial lighting the objective of a building without cooling plant was realized.
  The resulting final design was presented to the principal and the tenant for approval.

o Preparation of building specifications and construction drawings
Finally the design was completed with the development of construction drawings and building specifications. However, no more changes to the basic building design were made.

IDEF-0 process models representing the design of the Dynamic Office, Haarlem

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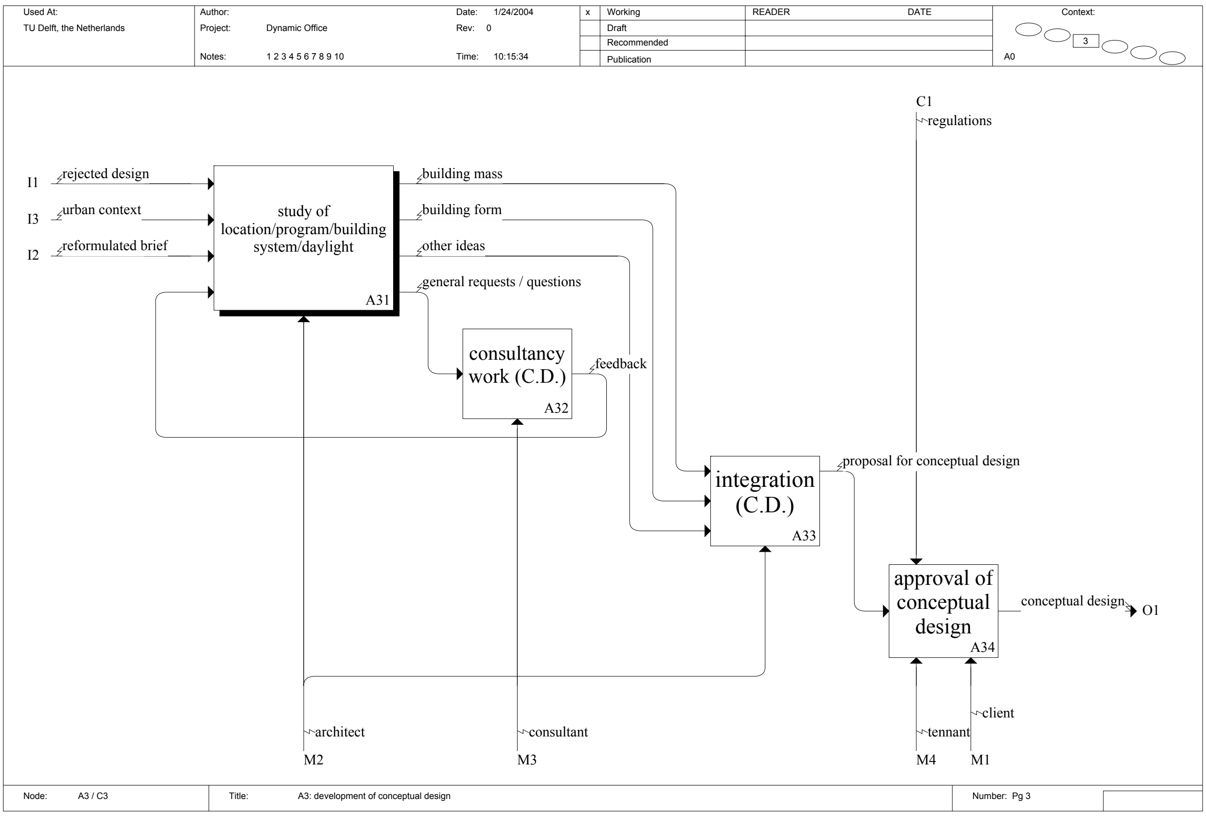
Publication
READER
DATE
Context:
TOP
C1
regulations
I2 urban context
I1 brief
previous building design process
A1
rejected design
study of feasibility
A2
feasibility
requirement: 150 degree-hours
reformulated brief
by-products
O2
development of conceptual design
A3
conceptual design
development of preliminary design
A4
relaxation to 180 degree-hours
preliminary design
analysis request: slope of facade?
development of final design
A5
final design
preparation for building construction
A6
construction drawings and specifications
O1
client
architect of earlier design project
architect
tennant
consultant
tools
M6
M4
M1
M2
M5
M3
Node: A0 / C2
Title: A0: design of the Dynamic Office
Number: Pg 2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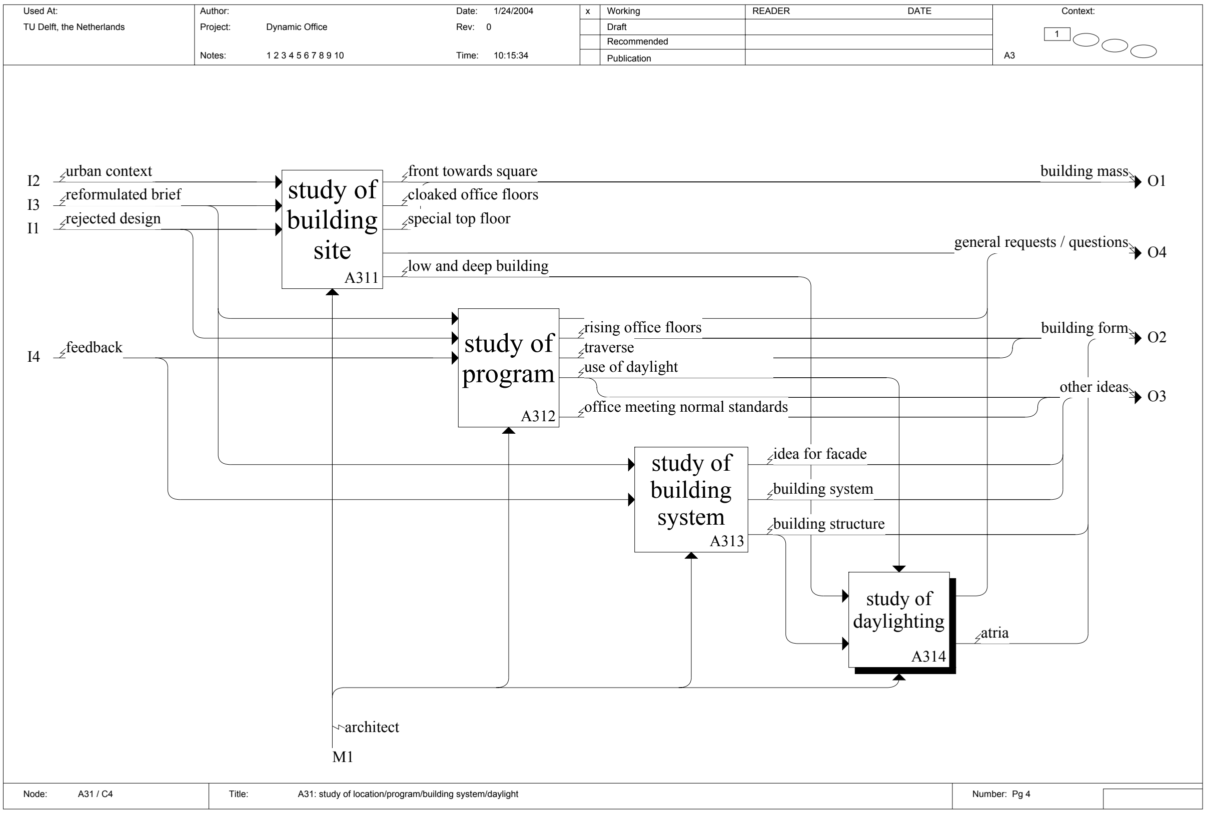
DATE
Context:
3
A0
C1
regulations
I1 rejected design
I3 urban context
I2 reformulated brief
study of location/program/building system/daylight
A31
building mass
building form
other ideas
general requests / questions
consultancy work (C.D.)
A32
feedback
integration (C.D.)
A33
proposal for conceptual design
approval of conceptual design
A34
conceptual design
O1
architect
consultant
tennant
client
M2
M3
M4
M1
Node: A3 / C3
Title: A3: development of conceptual design
Number: Pg 3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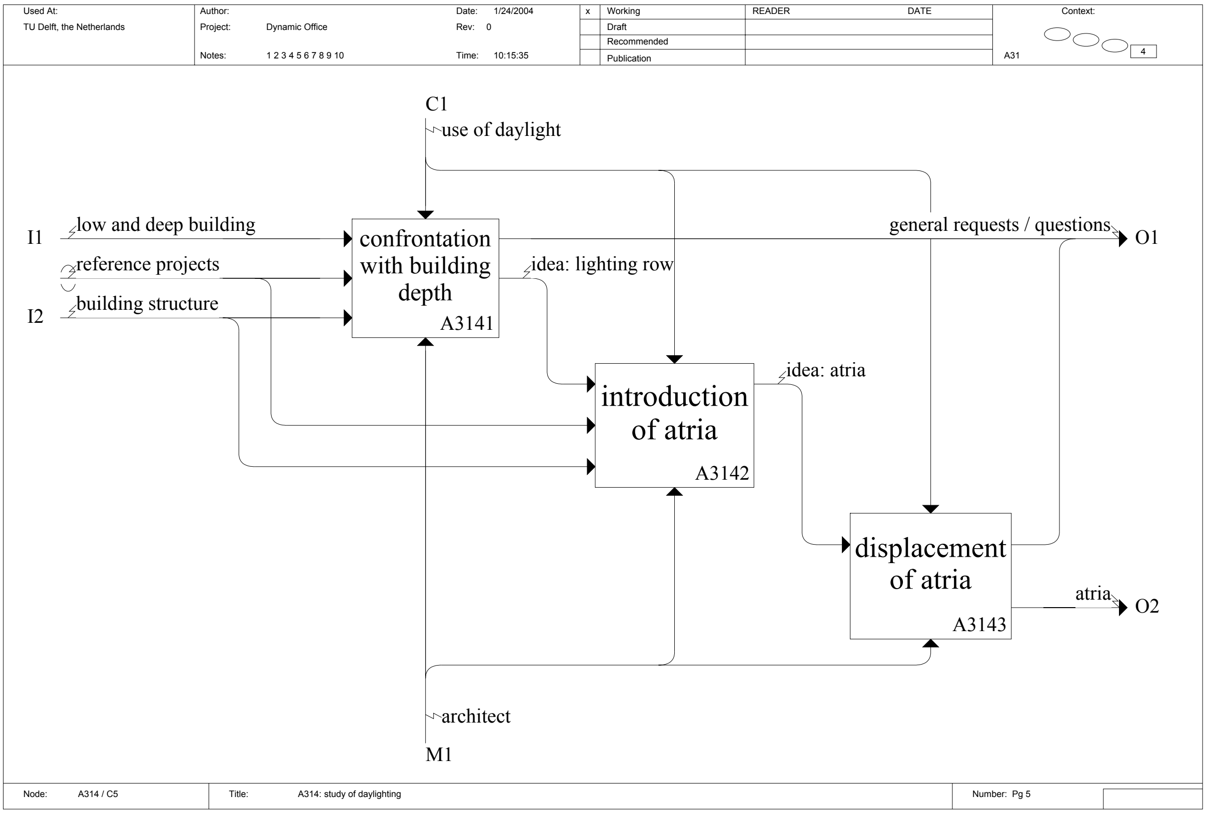
DATE
Context:
1
A3
I2
urban context
I3
reformulated brief
I1
rejected design
study of building site
A311
front towards square
cloaked office floors
special top floor
low and deep building
building mass
O1
general requests / questions
O4
I4
feedback
study of program
A312
rising office floors
traverse
use of daylight
office meeting normal standards
building form
O2
other ideas
O3
study of building system
A313
idea for facade
building system
building structure
study of daylighting
A314
atria
architect
M1
Node: A31 / C4
Title: A31: study of location/program/building system/daylight
Number: Pg 4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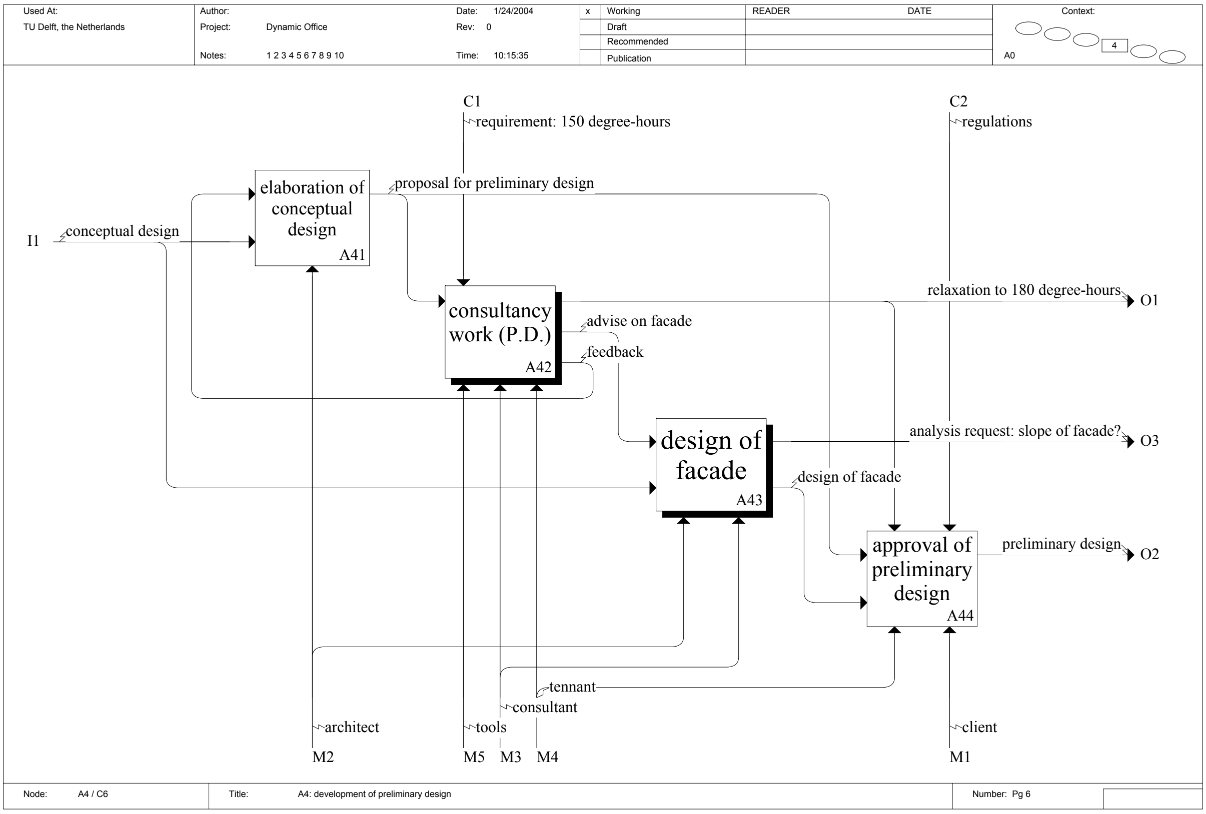
Recommended
Publication
READER
DATE
Context:
4
A31
C1
use of daylight
I1
low and deep building
reference projects
I2
building structure
confrontation with building depth
A3141
general requests / questions
O1
idea: lighting row
introduction of atria
A3142
idea: atria
displacement of atria
A3143
atria
O2
architect
M1
Node: A314 / C5
Title: A314: study of daylighting
Number: Pg 5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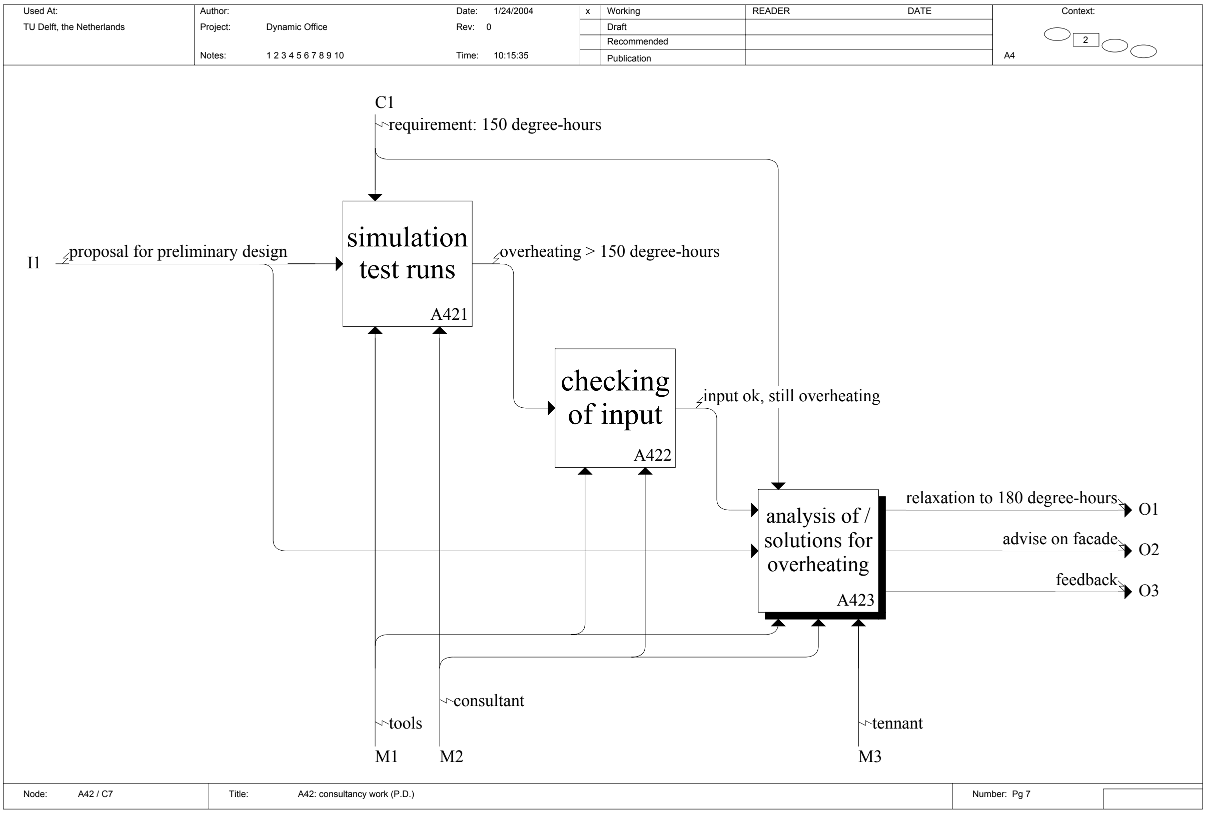
DATE
Context:
4
A0
C1
requirement: 150 degree-hours
C2
regulations
elaboration of conceptual design
A41
proposal for preliminary design
I1
conceptual design
consultancy work (P.D.)
A42
advise on facade
feedback
relaxation to 180 degree-hours
O1
design of facade
A43
analysis request: slope of facade?
O3
design of facade
approval of preliminary design
A44
preliminary design
O2
tennant
consultant
architect
tools
client
M2
M5
M3
M4
M1
Node: A4 / C6
Title: A4: development of preliminary design
Number: Pg 6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Recommended
Publication
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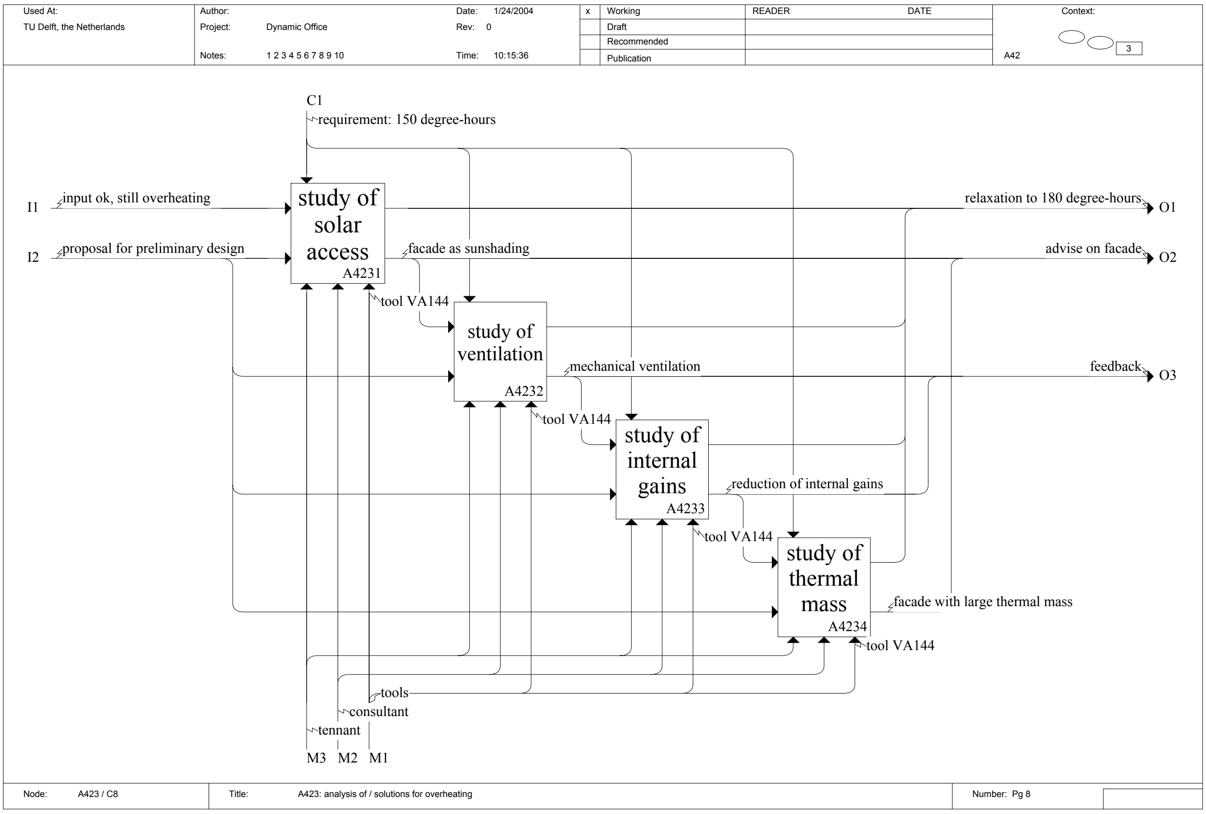
Context:
2
A4
C1
requirement: 150 degree-hours
I1
proposal for preliminary design
simulation test runs
A421
overheating > 150 degree-hours
checking of input
A422
input ok, still overheating
analysis of / solutions for overheating
A423
relaxation to 180 degree-hours
O1
advise on facade
O2
feedback
O3
consultant
tools
tennant
M1
M2
M3
Node: A42 / C7
Title: A42: consultancy work (P.D.)
Number: Pg 7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Recommended
Publication
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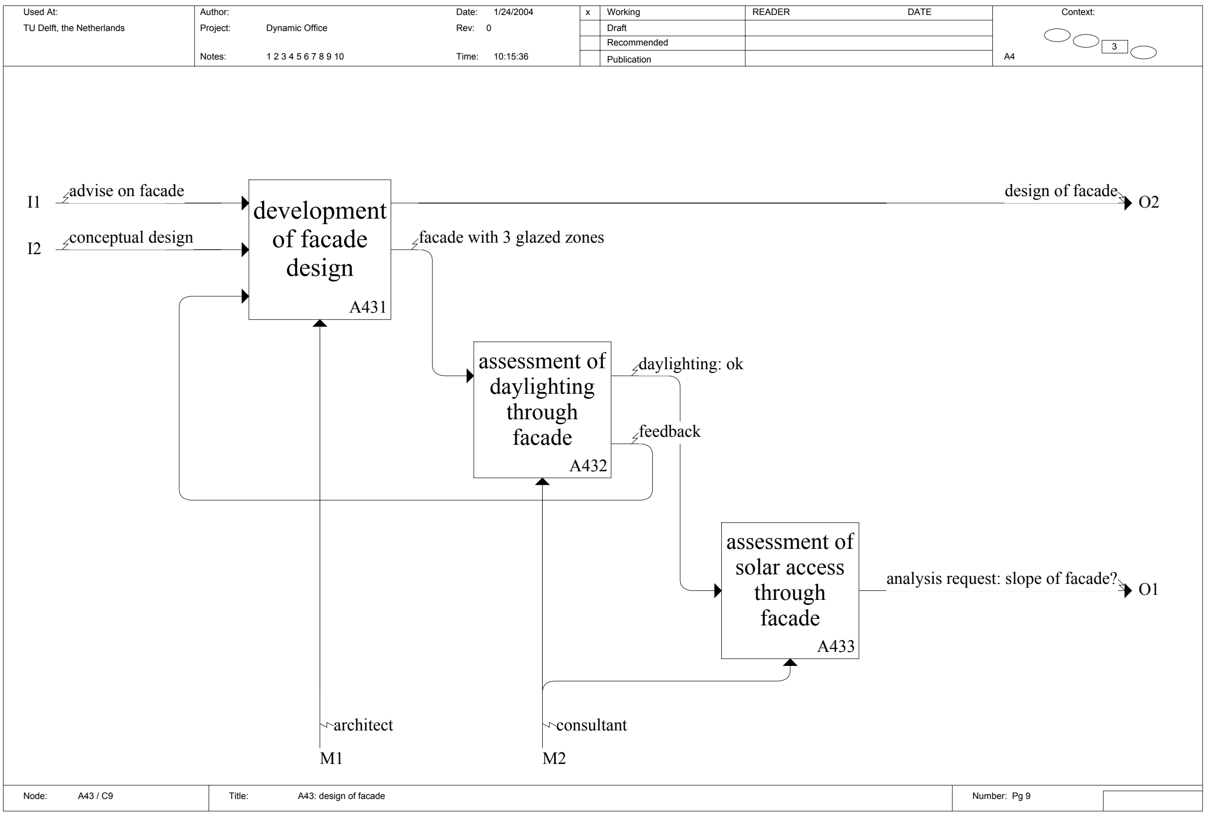
DATE
Context:
3
A42
C1
requirement: 150 degree-hours
I1
input ok, still overheating
I2
proposal for preliminary design
study of solar access
A4231
facade as sunshading
tool VA144
study of ventilation
A4232
mechanical ventilation
tool VA144
study of internal gains
A4233
reduction of internal gains
tool VA144
study of thermal mass
A4234
facade with large thermal mass
tool VA144
relaxation to 180 degree-hours
O1
advise on facade
O2
feedback
O3
tools
consultant
tennant
M3 M2 M1
Node: A423 / C8
Title: A423: analysis of / solutions for overheating
Number: Pg 8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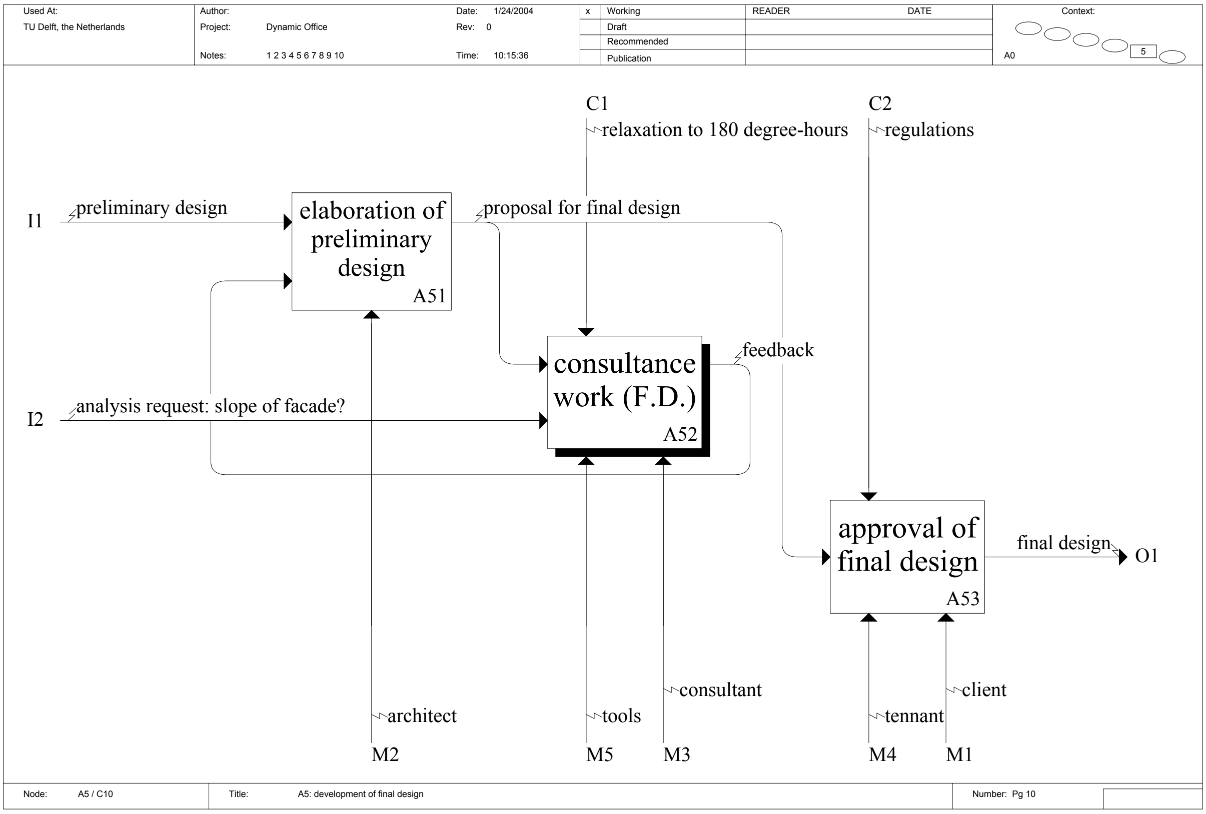
Draft
Recommended
Publication
READER
DATE
Context:
3
A4
I1
advise on facade
I2
conceptual design
development of facade design
A431
facade with 3 glazed zones
design of facade
O2
assessment of daylighting through facade
A432
daylighting: ok
feedback
assessment of solar access through facade
A433
analysis request: slope of facade?
O1
architect
M1
consultant
M2
Node: A43 / C9
Title: A43: design of facade
Number: Pg 9



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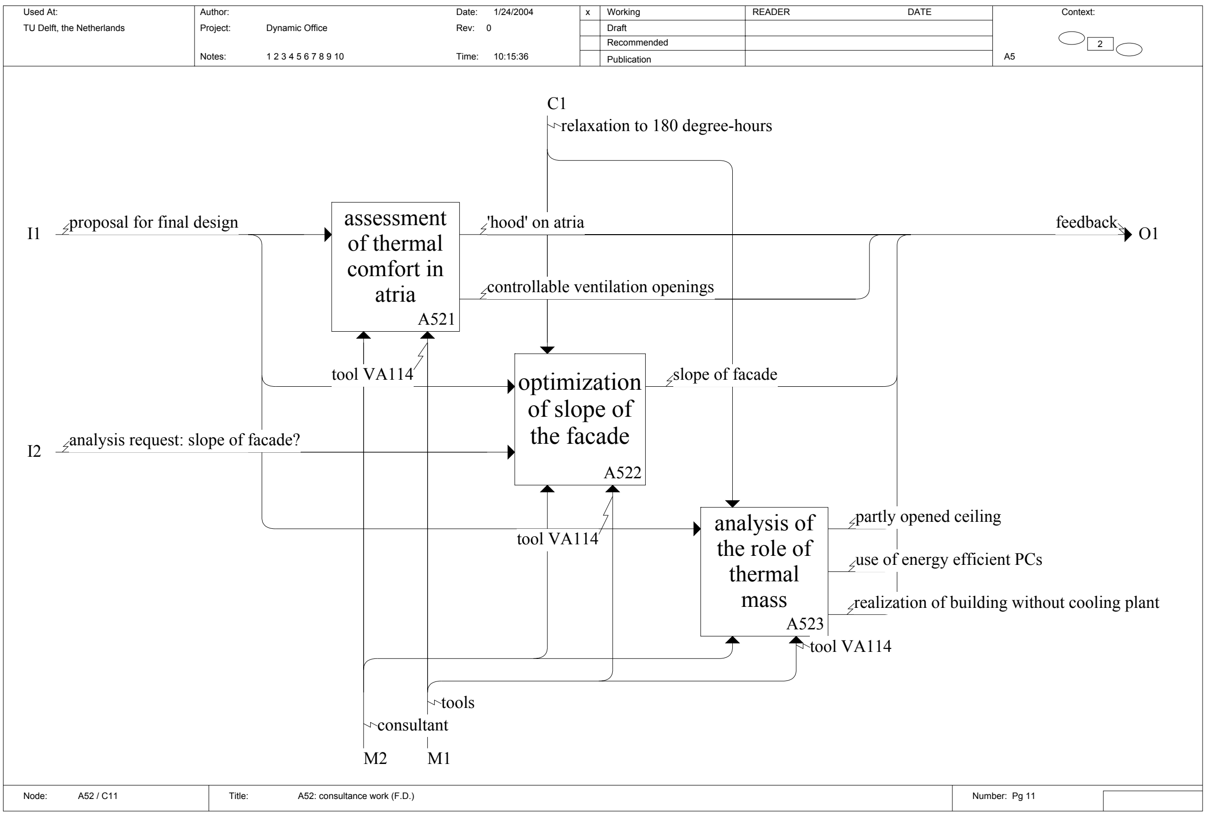
Context:
5
A0
C1
relaxation to 180 degree-hours
C2
regulations
I1
preliminary design
elaboration of preliminary design
A51
proposal for final design
consultance work (F.D.)
A52
feedback
I2
analysis request: slope of facade?
approval of final design
A53
final design
O1
architect
tools
consultant
tennant
client
M2
M5
M3
M4
M1
Node: A5 / C10
Title: A5: development of final design
Number: Pg 10



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DATE
Context:
2
A5
C1
relaxation to 180 degree-hours
I1
proposal for final design
assessment of thermal comfort in atria
A521
'hood' on atria
controllable ventilation openings
feedback
O1
tool VA114
optimization of slope of the facade
A522
slope of facade
I2
analysis request: slope of facade?
tool VA114
analysis of the role of thermal mass
A523
partly opened ceiling
use of energy efficient PCs
realization of building without cooling plant
tool VA114
tools
consultant
M2
M1
Node: A52 / C11
Title: A52: consultance work (F.D.)
Number: Pg 11

Appendix D: Questionnaire

For the survey project-specific questionnaires were developed. Since all questionnaires relate to individual projects, this appendix contain an example that is specific for one project as well. For similarity with the main text here the project of the Rijnland Office, one of the cases discussed in chapter three, has been selected.
The versions for architects and consultants were different, since they were tuned to the specific roles of the interviewees. This appendix only shows the questionnaire for the architect. The main difference with the version for the consultant is that the architect is asked for the role of the consultant (the consultant's input, the moment this input was received etc), while the consultant is asked more in-depth questions about the usage of computational tools.

[1ARCH]

Questionnaire for the architect of the Rijnland Office, Leiden, the Netherlands

Instruction:
This questionnaire consists of multiple-choice questions, supplemented with open questions where needed. Please select only one answer per question, unless the text specifically indicates that more than one option can be chosen. Please provide brief and concise answers to the open questions.

Architectural company:

1. How large is the company that designed the Rijnland Office?
   - ☐ 1-5 employees
   - ☐ 6-10 employees
   - ☐ 11-50 employees
   - ☐ more than 50 employees

2. How many years of experience does this company have with design projects?
   …………………

3. Can you please provide a few catchwords that describe the main focus of this company on each of the following areas?
   Type of projects the company designs: ……………………………………………
   Underlying thinking of the company: ……………………………………………
   Special expertise: ……………………………………………

Energy saving building components:

4. According to our data the following energy saving building components have been integrated into the design of the Rijnland Office: long term energy storage in the soil, heat pumps, low-temperature heating, high temperature cooling, heat exchangers, climate facade, daylighting systems, atrium. Is that correct?

☐ Yes
☐ No, the following energy saving building components are not integrated into the Rijnland Office:

…………………………………………………………………
………………………

☐ No, the following energy saving building components are missing from the list:
1. …………………………………………………………(reference: $ESBC_1$)
2. …………………………………………………………(reference: $ESBC_2$)

5. Can you indicate for each energy saving building component whether you have considered the use of alternatives instead of this component? If so, can you state which alternatives have been considered?

	No alternatives ↓	Yes, the following alternatives were considered ↓
Long-term storage in soil:	☐	☐ …………………………
Heat pumps:	☐	☐ …………………………
Low-temperature heating:	☐	☐ …………………………
High-temperature cooling:	☐	☐ …………………………
Heat exchangers:	☐	☐ …………………………
Climate facade:	☐	☐ …………………………
Daylighting system:	☐	☐ …………………………
Atrium:	☐	☐ …………………………
ESBC1:	☐	☐ …………………………
ESBC2:	☐	☐ …………………………

6. Can you indicate for each of the energy saving building components why of all options this specific component has been selected?

	↓ selection based on reference projects or earlier experience	↓ selection based on maximizing energy efficiency	↓ selection based on cost-benefit analysis	↓ selection based on other motivation (please specify)
Long-term storage in soil:	☐	☐	☐	☐ ………………..……………..…
Heat pumps:	☐	☐	☐	☐ ………………..……………..…
Low-temperature heating:	☐	☐	☐	☐ ………………..……………..…
High-temperature cooling:	☐	☐	☐	☐ ………………..……………..…
Heat exchangers:	☐	☐	☐	☐ ………………..……………..…
Climate facade:	☐	☐	☐	☐ ………………..……………..…
Daylighting system:	☐	☐	☐	☐ ………………..……………..…
Atrium:	☐	☐	☐	☐ ………………..……………..…
ESBC1:	☐	☐	☐	☐ ………………..……………..…
ESBC2:	☐	☐	☐	☐ ………………..……………..…

Brief explanation:

A number of questions concerns the moment of the design process in which specific activities take place. The research team acknowledges the fact that the design process is a dynamic process, and that activities might not always have clear boundaries. Nevertheless we ask that you use the following phasing (which is in common use):

F.S.: Feasibility study
C.D.: Conceptual design
P.D.: Preliminary design
F.D.: Final design
P.B: Preparation of building specifications and construction drawings

7. Can you indicate for each individual energy saving building component in which phase of the design process you decided to select this component?

Long-term storage in soil:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Heat pumps:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Low-temperature heating:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
High-temperature cooling:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Heat exchangers:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Climate facade:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Daylighting system:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
Atrium:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
ESBC1:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
ESBC2:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.

8. What was the main reason to select each energy saving building component in the phase you indicated in the previous question?

↓ previous to that phase there was insufficient information available
↓ in this phase there was enough freedom to integrate this component in the building design
↓ the energy efficiency of the building design had to be improved
↓ other motivation (please specify)

Long-term storage in soil:	☐	☐	☐	☐ …………………..……………..…
Heat pumps:	☐	☐	☐	☐ …………………..……………..…
Low-temperature heating:	☐	☐	☐	☐ …………………..……………..…
High-temperature cooling:	☐	☐	☐	☐ …………………..……………..…
Heat exchangers:	☐	☐	☐	☐ …………………..……………..…
Climate facade:	☐	☐	☐	☐ …………………..……………..…
Daylighting system:	☐	☐	☐	☐ …………………..……………..…
Atrium:	☐	☐	☐	☐ …………………..……………..…
ESBC1:	☐	☐	☐	☐ …………………..……………..…
ESBC2:	☐	☐	☐	☐ …………………..……………..…

Tools used in the architectural company:

9. Did the employees of the architectural company use specific tools to ensure that the Rijnland Office became an energy-efficient building? (multiple selection allowed)
   - ☐ No, there was no use of specific tools *(please continue with 13)*
   - ☐ Yes, we used the following checklist(s): ………………………………………
   - ☐ Yes, we used the following handbook(s): …………………………..………..
   - ☐ Yes, we used our own computational tool(s):
     1. ……………………………………………………………… $(Tool_x)$
     2. ……………………………………………………………… $(Tool_y)$
   - ☐ Yes, we used: ………………………………………………... (anything else)

10. Please indicate for each of these tools why it was used ? (multiple selection allowed)

	↓ to get an overview of energy saving building components	↓ to support a choice from a number of options	↓ optimalization of design parameters	↓ other usage (please specify)
Checklist:	☐	☐	☐	☐ ………………..…………..…
Handbook:	☐	☐	☐	☐ ………………..…………..…
$Tool_x$:	☐	☐	☐	☐ ………………..…………..…
$Tool_y$:	☐	☐	☐	☐ ………………..…………..…
Anything else:	☐	☐	☐	☐ ………………..…………..…

11. Did you think of using other tools instead of the ones you used? If so, can you state which alternatives have been considered?

	No alternatives ↓	Yes, the following alternatives were considered ↓
Checklist:	☐	☐ …………………………
Handbook:	☐	☐ …………………………
$Tool_x$:	☐	☐ …………………………
$Tool_y$:	☐	☐ …………………………
Anything else:	☐	☐ …………………………

12. If you did make a choice between different tools, why did you decide for the tool you used?

	↓ there was no choice between tools	↓ the tool used was the most accessible tool	↓ the tool used was the most suitable tool	↓ other motivation (please specify)
Checklist:	☐	☐	☐	☐ ………………..…………..…
Handbook:	☐	☐	☐	☐ ………………..…………..…
$Tool_x$:	☐	☐	☐	☐ ………………..…………..…
$Tool_y$:	☐	☐	☐	☐ ………………..…………..…
Anything else:	☐	☐	☐	☐ ………………..…………..…

Advice on energy-related aspects:

13. Did you contact a consultant for advice on energy-related aspects? If so, what is the name of the consultancy?
    - ☐ no, we did not contact a consultant *(please skip question 14 to 18)*
    - ☐ yes, we contact the following consultancy:
      name of company: ……………………………………………
      seat: ....………………………………………………..

14. In which phases of the design process did the consultant participate in the design process? (multiple selection allowed)
    ☐ F.S. ☐ C.D. ☐ P.D. ☐ F.D. ☐ P.B.

15. What was the contribution of the consultant to the building design process? (multiple selection allowed)
    - ☐ $Contribution_1$: suggest design alternatives
      Can you specify the design alternatives suggested by the consultant?
      …………………………………………………
    - ☐ $Contribution_2$: doing calculations for verification purposes
      Can you specify the type of verification involved?
      ☐ verification of expected energy efficiency
      ☐ verification of expected thermal comfort
      ☐ something else (please specify): ..……………………………
    - ☐ $Contribution_3$: optimalization of parameters of the building design and/or energy saving building component
      Can you specify the parameters that were optimized?
      …………………………………………………
    - ☐ $Contribution_4$: other contribution to the design process (please specify):
      ………………………………………………….

16. For which of the contributions listed in question 15 did the consultant employ a computational tool? (multiple selection allowed)
    ☐ $Contribution_1$ ☐ $Contribution_2$ ☐ $Contribution_3$ ☐ $Contribution_4$

17. Who made the decision to employ a computational tool?
    - ☐ Architect
    - ☐ Consultant
    - ☐ Client
    - ☐ Other party (please specify): ……………..…………..

18. In which phase of the design process did you get the results/feedback of the consultants efforts on each of the contributions?

$Contribution_1$:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
$Contribution_2$:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
$Contribution_3$:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.
$Contribution_4$:	☐ F.S.	☐ C.D.	☐ P.D.	☐ F.D.	☐ P.B.

Process management:

19. For the design of the Rijnland Office, were you able to reuse earlier experience regarding the selection and integration of energy saving buildings components that you obtained in previous design projects? If so, can you describe these previous projects and their consequences for the design of the Rijnland Office?
   ☐ No use of earlier projects/experiences
   ☐ Yes; the following previous projects had the following consequences for the Rijnland Office:
   ……………………………….....……→………………………………………
20. Was there any kind of 'Quality Assurance System' in place during the design of the Rijnland Office to ensure that the design process proceeded in an optimal and efficient way, and which ensured that decisions regarding the energy efficiency of the building design were made at the right moment, and based on sufficient information?
   ☐ No
   ☐ Yes, the following Quality Assurance System was used:
   …………………………………..

21. If you could repeat the design process of the Rijnland Office, would you decide on taking a different approach for energy-related aspects? If so, can you describe which aspects you would approach differently, and how you would approach them now?
   ☐ No
   ☐ Yes, I would approach the following in a different way:
   ……………………………………………………………………………………
   Do you think the different approach will cause new problems?
   ☐ Yes
   ☐ No

Remarks?

22. Do you have any further feedback, suggestions, and remarks on this questionnaire?
   ……………………………………………………………………………………
   ……………………………………………………………………………………

This is the end of this questionnaire. Thanks for you cooperation!

Appendix E: The Design Analysis Interface (DAI) Initiative

Detailed background information

The DAI-Initiative is a research project that focuses on the integration of building performance analysis and building design. A first stage of the research was carried out by a group of US universities[43] between September 2001 and September 2002, funded by the US Department of Energy (Augenbroe and de Wilde, 2003; Georgia Institute of Technology, 2003). Further stages of the DAI-Initiative are currently being planned in both the US and Europe.

The goal of the DAI-Initiative is to develop credible solutions to the integration of building performance analysis tools and the building design process. These solutions are to enable a more effective and efficient use of existing and emerging building performance analysis tools by building design and building engineering teams. Spearheads of the project are an improved functional embedding of performance analysis tools in the design process, increased quality control for building analysis efforts, and exploitation of the opportunities provided by the Internet (in particular the possibilities for collaboration of loosely coupled teams, allowing the execution of specific building performance analysis tasks by (remote) domain experts).

The DAI-Initiative starts from the premise that available solutions for integration based on building product modeling and standardization efforts alone will not be able to meet this objective for a number of reasons (Augenbroe and Eastman, 1998):

- current product models and standards are focused on data exchange; they do not take the process context into account and therefore are unable to deal properly with those issues of data transport that are related to process logic.
- current developments in building product models focus on single uniform (neutral) building models. Yet neutral models have some distinct disadvantages:
    1. interfaces between neutral models (containing all available data about a building) and specific tools (dealing with one performance aspect only) have to filter out the relevant information, making the creation of these interfaces overly complex (over-engineering);
    2. mapping data from one domain to another (e.g. from lighting to acoustics) might neither be possible, nor useful;
    3. neutral models bring in a problem related to ownership, maintenance and updating of the information in the product model;
    4. using neutral models might have severe implications for the building design process, imposing a rigid order for the use of tools and models.
- current product models and standards assume that all information about a building design is structured and can be stored in models. Yet some information might be unstructured, like ideas in the heads of the members of the design team etc.
- current product models assume that data transport can be automated; however, fully automated data transport eliminates the option of simplifying and abstracting data (an activity carried out by many experts working in design projects).

[43] Georgia Institute of Technology, Atlanta; Carnegie Mellon University, Pittsburgh; and University of Pennsylvania, Philadelphia

Yet in spite of these problems the DAI-Initiative takes it for essential to capitalize on all the efforts that have been invested in the development of building product models over the last decennium, and make maximum use of existing models and technology.

In order to overcome the above-mentioned problems to integration of building performance analysis tools and the building design process the DAI-Initiative aims to provide a layered approach to support the interaction between the building design process and building performance analysis tools. The approach aims for a data-pull mode rather than a data-push mode. In other words, the objective is to develop a mechanism that provides tools with the relevant information for carrying out an analysis task, rather than shipping all available data about a building design to the tool. This is realized by the development of a workbench that supports the analysis of building designs through a 'fat' interface between the original elements that are relevant in product modeling: the building design information and building performance tools. The workbench positions building design information and tools on opposite layers; the intermediate layers function as a scoping mechanism or filter to transfer relevant information only to the tool layer. The intermediate layers provide context to any interaction by capturing the relevant process and modeling aspects, each on a separate layer.

The first stage of the DAI-Initiative aims to establish a proof of concept prototype of a support environment that demonstrates how process scenarios can provide a logical point of entry to building design analysis, connecting building design information, building (aspect) models and building performance assessment tools.

Requirements Specification

The development of the DAI-Prototype has been guided by the following requirements. The specification of these requirements was done in an iterative manner, incorporating the findings from mock-up, scenario development, workshops, and actual prototype realization.

Overall Prototype Requirements

- In order to allow the DAI-Prototype to provide support for design professionals working in a team context, a web based application is preferred. This allows the use of the internet for data exchange and communication. It should be noted that the components of a web based application can also be installed on an intranet or even on a stand-alone computer, thereby combining server and client into one machine.
- The DAI-Prototype needs to incorporate a module for easy design, adjustment, enactment and documentation of processes / scenarios.
- In order to demonstrate the credibility of the solutions to the integration of building analysis tools and the building design process as put forward by the DAI-Initiative, the prototype needs to contain a number of real building performance assessment tools embedded in the tool layer. In order to demonstrate the universality of the system it was found to be advantageous if at least two different tools, both assessing different performance aspects, could be incorporated in the prototype.

Process Modeling Requirements

As the initial research focuses on the scenario layer, the selection of a suitable process modeling method is the first step towards building the actual prototype. The following requirements have been identified as being relevant in selecting such a method:

- The process modeling method must be able to capture process dependencies as well as temporal logic;

- It should be suitable to support loosely coupled teams as are common in building design projects (allowing remote actors, dispersed teams etc);
- It must be based on a task centric, not on a data centric paradigm;
- It must allow to focus on (relatively) short process windows;
- It should provide a graphical process representation;
- The method should result in process models that can easily be understood by end users.

Preferably existing commercial software is to be used. It will be advantageous if the process module allows to define processes in a short timeframe, and could initiate (call) other applications that reside in other layers of the workbench.

Requirements for Links Between Scenario and Adjacent Layers

The scenario layer will allow the user of the workbench to design and subsequently execute an analysis process. This process can be designed according to the expertise, skills and individual preferences of the expert doing the analysis. The process will not only contain the basic analysis tasks, but related steps like data collection, selection of climate conditions, the selection of a suitable physical model, population of models, etc. as well. However, in the DAI-Prototype the interaction of the scenario layer with the adjacent layers (model layer and tool layer) will be restricted to the core of the analysis work only, which is captured in the analysis functions. This leads to the following requirement:

- An analysis function is the scoping mechanism for specific analysis tasks. It comes with a schema that defines the data needed to call this function, as well as with a pre-made interface between this data schema and a building performance analysis tool that is qualified to do the analysis. The data schema allows to link the scenario layer to the model layer, and ultimately to the building information layer above, in a tool-independent manner. The interfaces to qualifying tools link the upper layers to the tool layer below.

As information exchange is a key factor in the communication between the layers of the workbench, the following requirements have been identified regarding the description of data:

- The building model layer must contain minimalistic product models that capture the essential elements - from a design analysis point of view – of the analysis functions. These analysis function models must be populated from the building design information layer. For the time being however this is not to be covered by the DAI-Prototype. Instead, hand-populated models will be made available on the building model layer;
- An internal interface is needed that translates the data contained in the populated minimalistic product model to input for a suitable building performance analysis tool that resides on the tool layer;
- For the data transport between the building model layer and tool layer XML technology (Refsnes Data, 2002) is the preferred option. XML has a lot of merits for storing data as a structured document and for displaying data on the web (important in remote-collaboration). XML is becoming the standard way to identify and describe data on the web. XML is a human-readable, machine-understandable, general syntax for describing hierarchical data, applicable to a wide range of applications, databases, e-commerce, Java, web-development etc. With these strong points, many applications in the building industry are already starting to use XML technology to import, output and store data.

Requirements for Analysis Functions

Analysis functions need to capture the atomic, recurring analysis tasks that are embedded in typical analysis scenarios, where those typical analysis scenarios are used to react to typical analysis requests originating from the design process.

- All analysis functions will concern a specific performance aspect (thermal, lighting, acoustics, air flow etc) and a specific building or building sub-system. It is therefore assumed that analysis functions are always specific to one performance aspect only, and are fired to predict the performance of one specific building. In case different performance aspects need to be assessed, different analysis functions can be fired. In case different design options need to be assessed the same analysis function can be fired for each design option.
- Analysis functions need to be related to specific performance indicators, since the same performance aspect can be quantified in different ways. For instance thermal comfort can be quantified using the number of hours that the average air temperature exceeds a certain threshold value, or with a more complicated performance indicator like PMV values as defined by Fanger (1970). Both methods of predicting thermal performance have their own metrics, which should be reflected by different, specific analysis functions. However, all predictions of thermal comfort in one room according to Fanger PMV should be able to start from the same analysis function, which then must have an option to set parameters of the analysis in order to match the conditions as specified in the design analysis request.
- The definition of analysis functions should result in a manageable set of analysis functions that can be used to unambiguously specify which performance aspect is to be quantified, using what performance indicator, while allowing a range of buildings as large as possible to be assessed, and while maintaining the freedom of changing parameters of the analysis.

Appendix F: Example of an Analysis Function: Energy Efficiency

1. Description of the analysis function in informal standard format

AF NAME:	'analyze efficient use of energy for an office cell of type X'
VERSION:	created December 2001; last modified may 2003

SYSTEM:	
sub –systems:	**assumptions:**
1. internal air zone (3.6 x 2.7 x 5.4)	complete mixing, no stratification, one average temperature
2. external air zone	complete mixing, no stratification, one average temperature; all data dependent on location + climate (see TEST)
3. internal construction elements (0.300 m of concrete)	have thermal capacity, thermal resistance, 1-D heat flows; heat exchange with air zones through convection and radiation
4. façade (30% glazing)	thermal capacity, thermal resistance, 1-D heat flows; heat exchange with air zones through convection and radiation
5. glazing system (0.006 glass, 0.012 cavity, 0.006 glass)	thermal capacity, thermal resistance, 1-D heat flows, transmittance, reflection; heat exchange with air zones through convection and radiation
6. furniture (2 desks, 2 chairs)	assumed as added thermal mass to air zone only
7. HVAC-system	"idealized" system

system boundaries:		
position:	**type of boundary:**	**throughput:**
a. at symmetry axis of construction elements	adiabatic boundary condition	none
b. enclosing external air zone	formal boundary	climate data, according to TEST

internal system variables:

head load, according to TEST; HVAC settings, according to TEST

OBSERVED STATES:

observation period:

duration:	**per week:**	**per day:**	**special notes:**
365 days (one year)	monday - friday	8:00AM – 6:00PM	discard holidays etc

observation time step:	**observed states:**
per hour	heating load per year, cooling load per year

TEST:

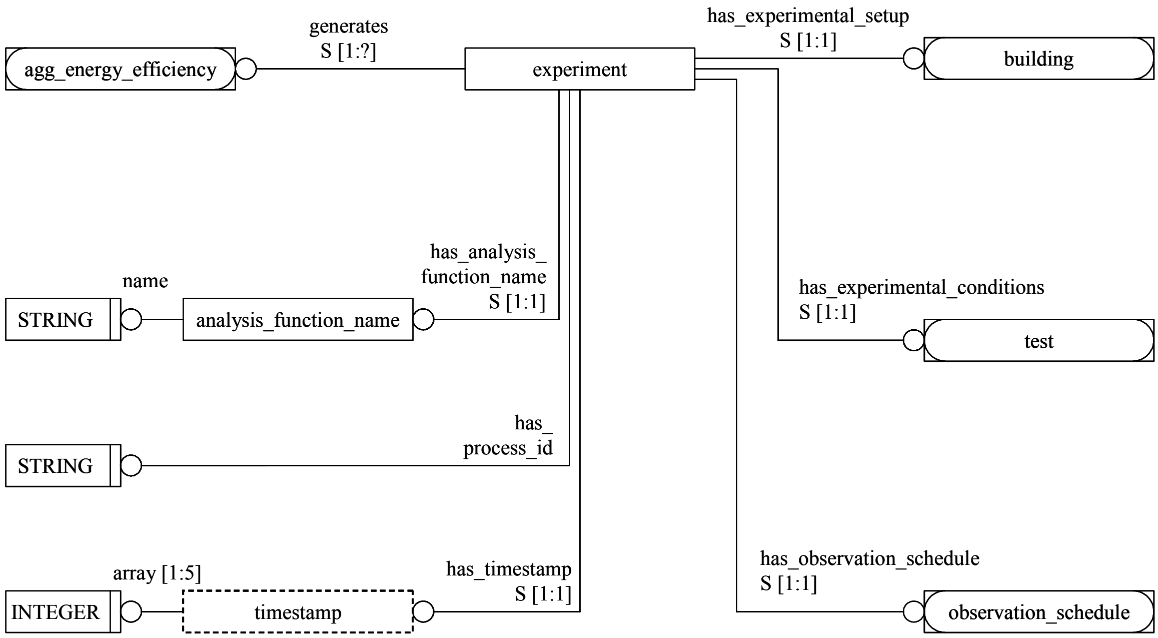
HVAC and heat load settings period:	cooling setpoint:	heating setpoint:	int. heat load:
monday-friday 0:00AM–8:00AM	off	10.0°C	none
monday-friday 8:00AM–6:00PM	22.5°C	19.5°C	2 persons, 2 PCs, lighting
monday-friday 6:00AM–24:00PM	off	10°C	none
saturday-sunday o:00AM–24:00PM	off	10°C	none

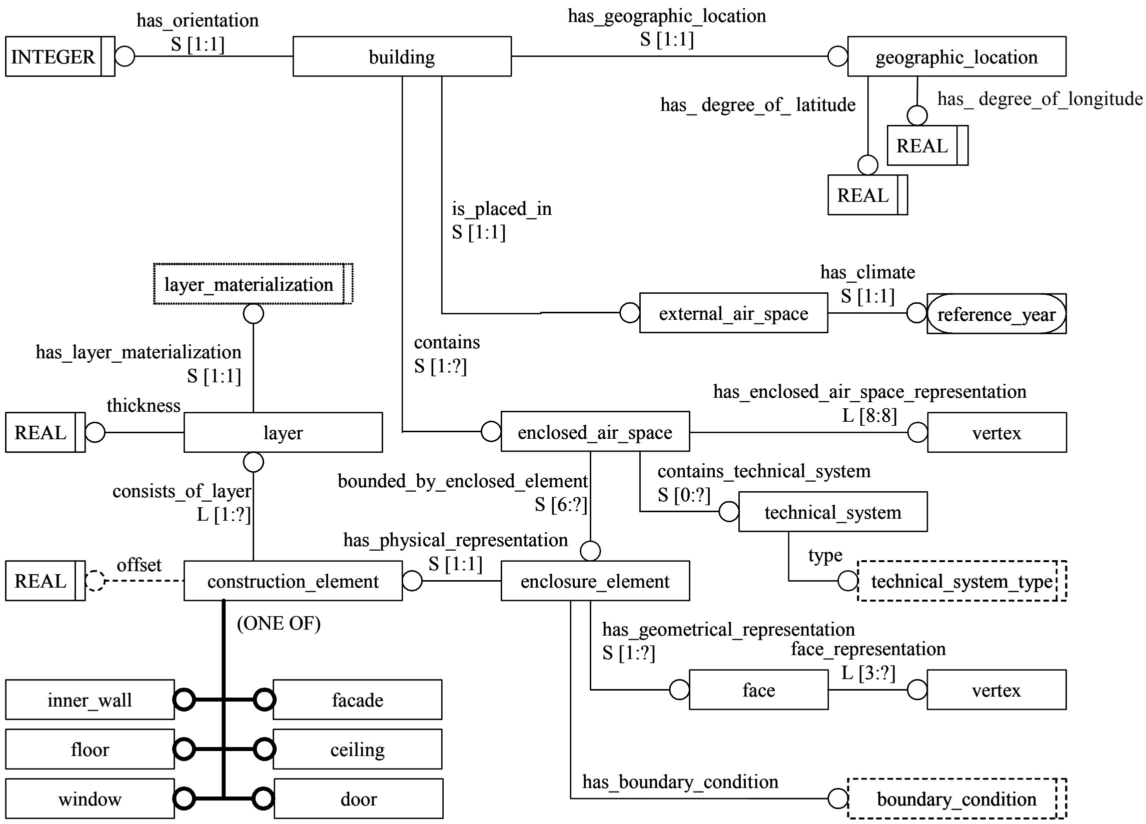
air exchange rate:	climate data:
constant, at 1.0 h^{-1}	according to TMY-2 data for Atlanta, GA, USA

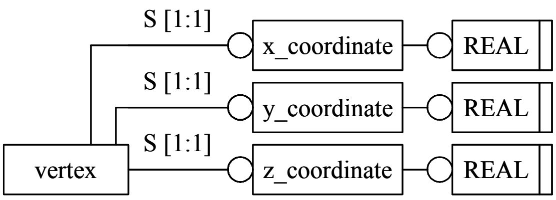
AGGREGATION OF OBSERVED STATES:

a = heating load per year (observed state 1)	c = heating load per year for reference case Z
b = cooling load per year (observed state 2)	d = heating load per year for reference case Z
e = a + b	f = c + d
PI = e/f	

2. Corresponding EXPRESS-G diagram



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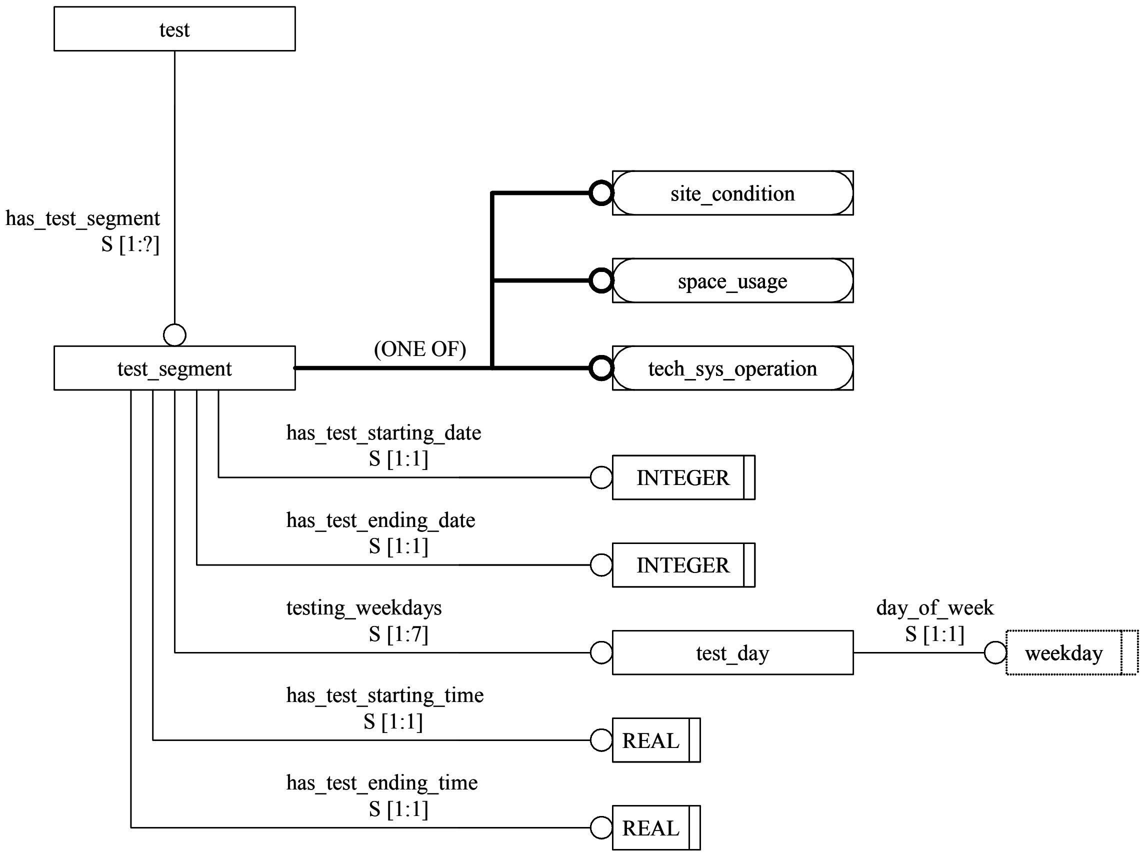
S [1:1]
vertex
z_coordinate
REAL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(ONE OF)
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S [1:1]
INTEGER
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S [1:7]
test_day
day_of_week
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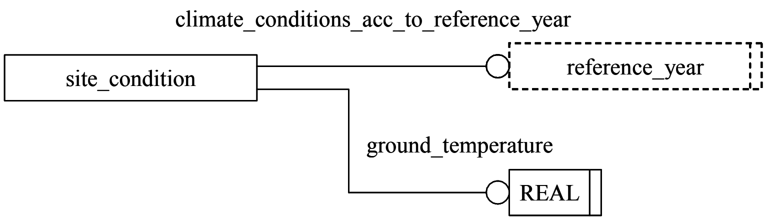
has_test_ending_time
S [1:1]
REAL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site_condition
reference_year
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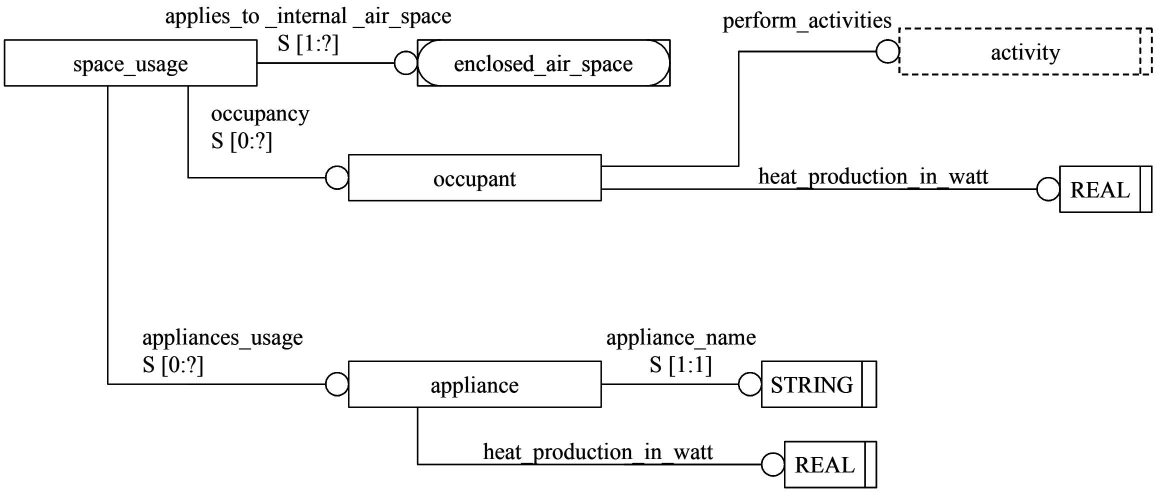
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enclosed_air_space
perform_activities
activity
occupancy
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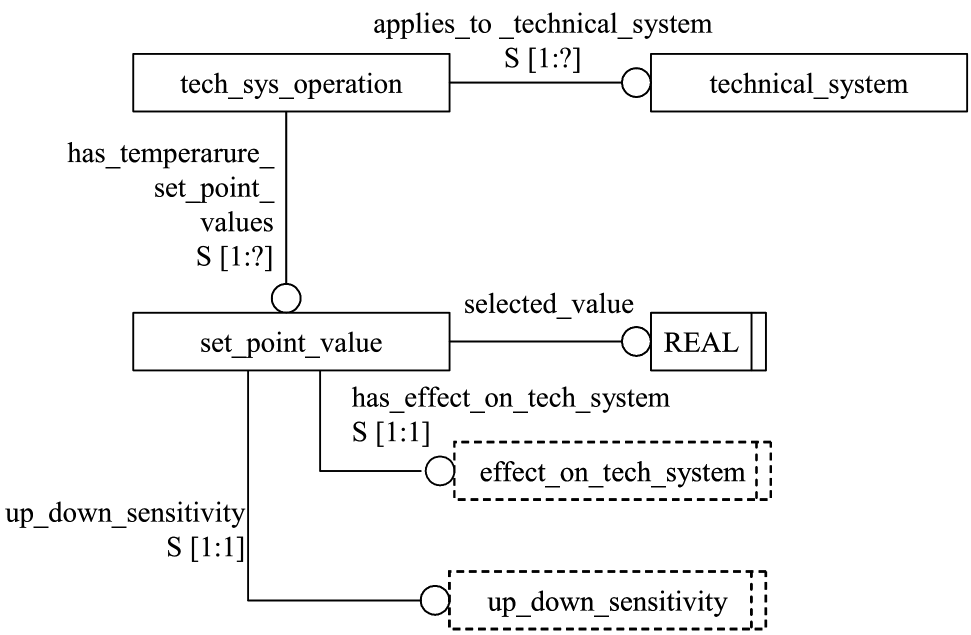
REAL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selected_value
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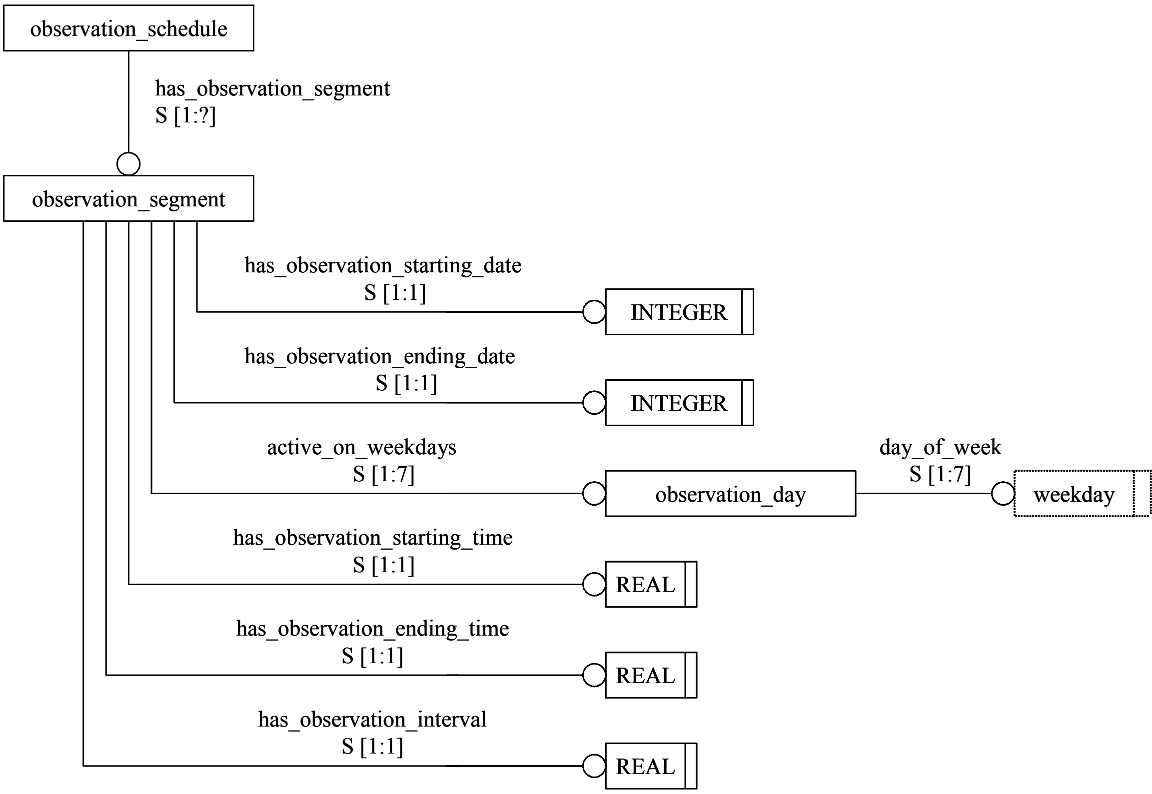
up_down_sensitivity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INTEGER
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observation_day
day_of_week
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weekday
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has_observation_ending_time
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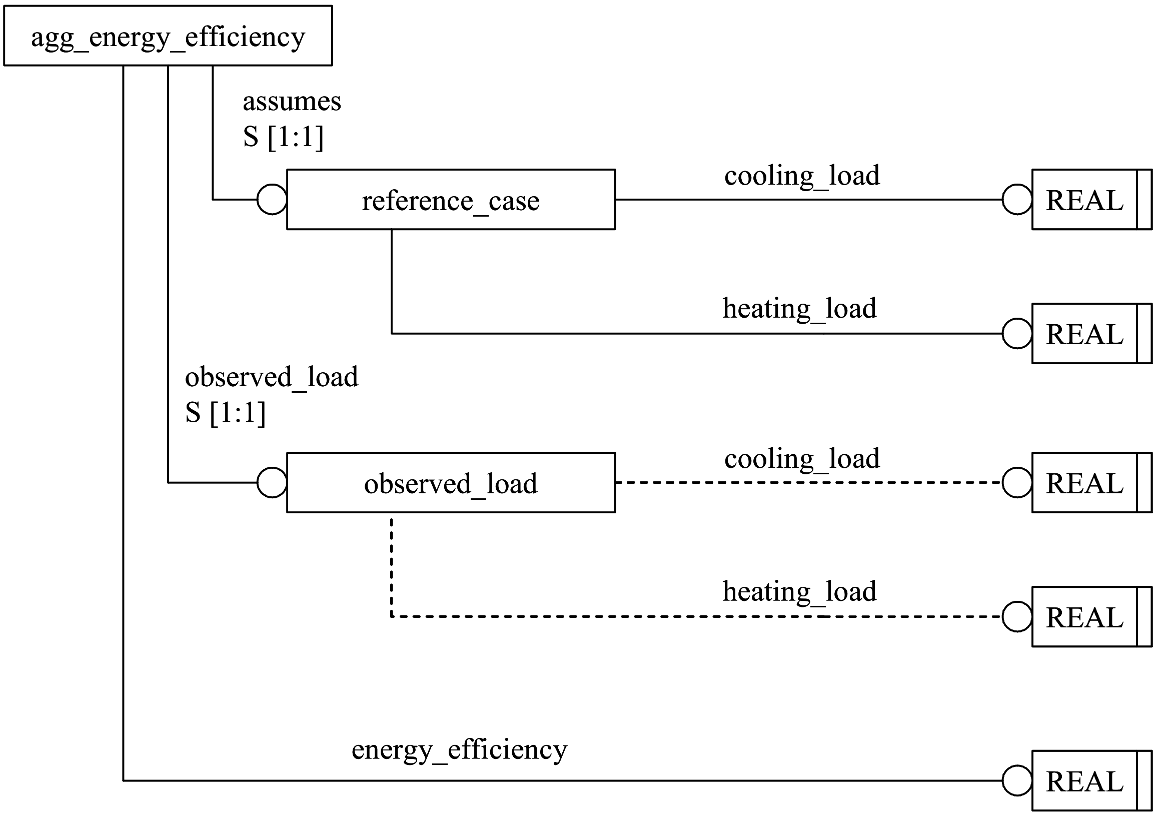
S [1:1]
REAL


agg_energy_efficiency
assumes
S [1:1]
reference_case
cooling_load
REAL
heating_load
REAL
observed_load
S [1:1]
observed_load
cooling_load
REAL
heating_load
REAL
energy_efficiency
REAL

3. Corresponding EXPRESS code

```
SCHEMA analysis_function_for_energy_efficiency;
(* version dated april 19 2002 *)

(* type definitions *)

TYPE activity = ENUMERATION OF (physical_work, office_work, sport, rest);
END_TYPE;

TYPE boundary_condition = ENUMERATION OF (external, symmetry, translation_symmetry,
slab_on_ground);
END_TYPE;

TYPE effect_on_tech_system = ENUMERATION OF (on, off);
END_TYPE;

TYPE layer_materialization = ENUMERATION OF (cavity, concrete, double_glazing, glasswool,
gypsum, low_e_glazing, single_glazing, open_space, pv_array);
END_TYPE;

TYPE reference_year = ENUMERATION OF (atlanta, amsterdam, michigan, philadelphia, pittsburgh,
washington);
END_TYPE;

TYPE technical_system_type = ENUMERATION OF (heating, cooling, ventilation, lighting,
solar_shading);
END_TYPE;

TYPE timestamp = ARRAY [1:5] of INTEGER;
END_TYPE;

TYPE up_down_sensitivity = ENUMERATION OF (up, down);
END_TYPE;

TYPE weekday = ENUMERATION OF (monday, tuesday, wednesday, thursday, friday, saturday,
sunday);
END_TYPE;

(* building *)

ENTITY vertex;
       x_coordinate   : REAL;
       y_coordinate   : REAL;
       z_coordinate   : REAL;
END_ENTITY;

ENTITY layer;
       has_layer_thickness          : REAL;
       has_layer_materialization    : layer_materialization;
END_ENTITY;

ENTITY construction_element
       SUPERTYPE OF ( ONEOF ( inner_wall, floor, window, facade, ceiling, door )  ) ;
       consists_of_layer            : LIST [1 : ?] OF layer;
       offset                       : OPTIONAL REAL;
END_ENTITY;

ENTITY inner_wall
       SUBTYPE OF (construction_element);
END_ENTITY;

ENTITY floor
       SUBTYPE OF (construction_element );
END_ENTITY;

ENTITY window
       SUBTYPE OF (construction_element );
END_ENTITY;

ENTITY facade
       SUBTYPE OF (construction_element );
END_ENTITY;

ENTITY ceiling
       SUBTYPE OF (construction_element );
END_ENTITY;
```

```
ENTITY door
       SUBTYPE OF (construction_element );
END_ENTITY;

ENTITY face;
       face_representation          : LIST [3 : ?] OF vertex;
END_ENTITY;

ENTITY enclosure_element;
       has_geometrical_representation       : SET [1 : ?] OF face;
       has_boundary_condition       : boundary_condition;
       has_physical_representation  : SET [1 : 1] OF construction_element;
END_ENTITY;

ENTITY technical_system;
       has_technical_system_type    : technical_system_type;
END_ENTITY;

ENTITY enclosed_air_space;
       has_enclosed_air_space_representation       : LIST [8 : 8] OF vertex;
       contains_technical_system           : SET [0 : ?] OF technical_system;
       bounded_by_enclosure_elements       : SET [6 : ?] OF enclosure_element;
END_ENTITY;

ENTITY external_air_space;
       has_climate                  : reference_year;
END_ENTITY;

ENTITY geographic_location;
       has_longitude                : REAL;
       has_latitude                 : REAL;
END_ENTITY;

ENTITY building;
       has_geographic_location              : SET [1 : 1] OF geographic_location;
       has_external_air_space       : SET [1 : 1] OF external_air_space;
       has_enclosed_air_space       : SET [1 : 1] OF enclosed_air_space;
       has_orientation                      : INTEGER;
END_ENTITY;

(* test *)

ENTITY test_day;
       day_of_week                  : weekday;
END_ENTITY;

ENTITY test_segment
       SUPERTYPE OF ( ONEOF ( site_condition, space_use, tech_sys_operation ) ) ;
       has_test_starting_day_of_year_number : INTEGER;
       has_test_ending_day_of_year_number   : INTEGER;
       testing_weekdays                     : SET [1 : 7] OF test_day;
       has_test_starting_time               : REAL;
       has_test_ending_time                 : REAL;
END_ENTITY;

ENTITY site_condition
       SUBTYPE OF (test_segment);
       climate_conditions_acc_to_ref_year   : reference_year;
       ground_temperature                   : REAL;
END_ENTITY;

ENTITY occupant;
       performs_activity                    : activity;
       heat_production_in_watt                      : REAL;
END_ENTITY;

ENTITY appliance;
       appliance_name                       : STRING;
       heat_production_in_watt                      : REAL;
END_ENTITY;

ENTITY space_use
       SUBTYPE OF (test_segment);
       applies_to_enclosed_air_space : SET [1 : 1] OF enclosed_air_space;
       occupancy                    : SET [0 : ?] OF occupant;

       appliance_usage                      : SET [0 : ?] OF appliance;
END_ENTITY;
```

```
ENTITY set_point_value;
       selected_value                : REAL;
       has_up_down_sensitivity              : up_down_sensitivity;
       has_effect_on_tech_system     : effect_on_tech_system;
END_ENTITY;

ENTITY tech_sys_operation
       SUBTYPE OF (test_segment);
       applies_to_technical_sytem           : SET [1 : 1] OF technical_system;
       has_temperature_set_point_values     : SET [1 : 2] OF set_point_value;
END_ENTITY;

ENTITY test;
       has_test_segment              : SET [1 : ?] OF test_segment;
END_ENTITY;

(* observation schedule *)

ENTITY observation_day;
       day_of_week                   : weekday;
END_ENTITY;

ENTITY observation_segment;
       has_observation_starting_day_of_year_number : INTEGER;
       has_observation_ending_day_of_year_number   : INTEGER;
       active_on_weekdays                          : SET [1 : 7] OF observation_day;
       has_observation_starting_time               : REAL;
       has_observation_ending_time                 : REAL;
       has_observation_interval                    : REAL;
END_ENTITY;


ENTITY observation_schedule;
       has_observation_segment                            : SET [1 : ?] OF
observation_segment;
END_ENTITY;

(* aggregated energy efficiency *)

ENTITY reference_case;
       reference_case_name                  : STRING;
       cooling_load                         : OPTIONAL REAL;
       heating_load                         : OPTIONAL REAL;
END_ENTITY;

ENTITY observed_load;
       cooling_load                         : OPTIONAL REAL;
       heating_load                         : OPTIONAL REAL;
END_ENTITY;

ENTITY agg_energy_efficiency;
       assumes                              : SET [1 : 1] OF reference_case;
       observes_load                        : OPTIONAL SET [1 : 1] OF observed_load;
       energy_efficiency                    : OPTIONAL REAL;
END_ENTITY;

(* experiment *)

ENTITY analysis_function_name;
       name                          : STRING;
END_ENTITY;

ENTITY experiment;
       has_experimental_setup        : SET [1 : 1] OF building;
       has_experimental_conditions   : SET [1 : 1] OF test;
       has_observation_schedule      : SET [1 : 1] OF observation_schedule;
       generates                     : SET [1 : 1] OF agg_energy_efficiency;
       has_analysis_function_name    : SET [1 : 1] OF analysis_function_name;
       has_process_id                : STRING;
       has_timestamp                 : timestamp;
END_ENTITY;

END_SCHEMA;
```

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Curriculum Vitae

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Academic education
1989-1995: Study of Architecture, Delft University of Technology, Delft, the Netherlands; Master thesis in Building Physics: 'The Solar Garden House: a preliminary study on the efficiency of a new concept for low-energy design'.
1996-2001: Ph.D.-Student with Delft University of Technology, Building Physics Group, Delft, the Netherlands; appointment as Research Assistant at Delft University of Technology, Building Physics Group (3/10) and as Visiting Researcher with the Energy research Centre of the Netherlands (ECN), Unit Renewable Energy in the Built Environment, Petten, the Netherlands (7/10)

Appointments
1995-1996: Freelance Researcher with Delft University of Technology, Building Physics Group
1996-2001: Ph.D.-Student with Delft University of Technology and ECN (see above)
2001-2002: Research Scientist I, Design Analysis Integration - Initiative, Georgia Institute of Technology, College of Architecture, Doctoral Program, Atlanta, Georgia, USA
2002-present: Research Scientist with TNO Building and Construction Research, Sustainable Energy and Buildings, Delft, the Netherlands

Professional activities
Member of the International Building Performance Simulation Association (IBPSA), the Dutch Flemish Building Physics Association (NVBV), and the Dutch Technical Association for Installations in Buildings (TVVL). Associate member of ASHRAE, the American Society for Heating, Refrigerating and Air-conditioning Engineers .

Prizes and honorary positions
IBPSA Outstanding young contributor award 2003; member of scientific committee of Building Simulation 2003, Eindhoven, the Netherlands.

Publications
Currently 2 articles in international journals (plus 2 articles accepted for publication); 17 peer-reviewed papers in proceedings of international conferences; 7 peer-reviewed publications in Dutch; 10 technical reports.