Towards the Integration of Simulation into the Building Design Process

Christoph Andreas Morbitzer Dipl.-Ing., M.Sc.

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Energy System Research Unit
Department of Mechanical Engineering
University of Strathclyde

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ABSTRACT

This thesis is concerned with the integration of simulation into the building design process to give designers a better understanding how design decisions influence the energy and environmental performance of a building, therefore increasing the awareness for these issues during the complex decision making process of the contemporary design process.

A concept was developed for a simulation supported design process (SSDP), which is based on the RIBA (Royal Institute of British Architects) Design Plan of Work and identifies for different building design stages appropriate simulation exercises. The implementation concept for the SSDP was to use the same simulation engine throughout the design process, but develop interfaces and performance analysis methods which address the requirements at different building design stages (typical users, potential time constrains, etc.).

To enable the creation of advanced simulation models at the Outline Design Stage the ODS-Interface was developed. This is intended for use by architects, who were identified as main users of the program. It utilizes a Database Management System in order to support the various data processing functions that need to be carried out during the application of an advanced simulation program. In addition a CAD tool is used for the specification of the simulation model geometry. The CAD drawing is also used to indicate zones or surfaces during the model attribution process.

Further research had the aim of enhancing the analysis of performance predictions obtained from a simulation exercise. This resulted in the development of an Integrated Performance View (IPV) for early design stages and for the application by non-simulation experts. To support simulation specialists at later, detailed design stages, data mining was introduced for the in-depth analysis of performance predictions obtained from a simulation exercise. Clustering was identified as a particularly useful technique. Barriers for the application of data mining in conjunction with building simulation were also identified and discussed.

Three case studies are presented to show how research and development described in the thesis can support design decision making that considers and addresses energy and environmental issues. The case studies show how the application of simulation can result in a more informed decision making process and an improved design quality. Finally the outcome of a survey is described which provides insight into how designers regard the use of simulation in the building design process. The survey emphasises the fact that research presented in this thesis was successful in contributing to the integration of building simulation into the building design process.

ACRONYMS

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BDA	Building Design Advisor
BMS	Building Management Systems
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CFD	Computational Fluid Dynamics
CIBSE	Charted Institution of Building Services Engineers
COMBINE	Computer Models for the Building Industry in Europe
DBMS	Database Management Systems
DDS	Detailed Design Stage
DDSS	Design Decision Support Systems
DETR	Department of Environment, Transport and the Regions
DOE	Department of Energy
DTLR	Department of Transports, Local Governments, Regions
EADS	Energy Design Advise Scheme
EEBPP	Energy Efficiency Best Practice Programme
EEDDSS	Energy and Environmental Design Decision Support Systems
ERM	Entity Relationship Model
ESRU	Energy Systems Research Unit
HVAC	Heating, Ventilation, Air Conditioning
IAI	International Alliance for Interoperability
IFC	Industry Foundation Class
IPV	Integrated Performance View
ISO	International Standard Organization
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
ODS	Outline Design Stage
PFI	Private Finance Initiative
PPP	Public Private Partnership
QA	Quality Assurance
RIBA	Royal Institute of British Architects

SDS	Scheme Design Stage
SESG	Scottish Energy Systems Group
SQL	Standard Query Language
SSDP	Simulation Supported Design Process
STEP	Standard for Exchange of Product Data
UoD	Universe of Discourse

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CHAPTER 1

INTRODUCTION

1.1 The evolution of buildings and changes in the building design process

1.1.1 The evolution of buildings

Most people nowadays live (at least in developed countries) in buildings where the environmental conditions are controlled by adjusting room temperatures, luminance levels and ventilation rates. The type and degree of control available varies, depending on aspects such as the building usage, the climatic conditions and the technical standards of the country where the building was constructed. Nevertheless, in principle it is now possible to provide any environmental condition in a building independent of the climatic conditions where it is located. This was not always the case: buildings have changed over time.

The first buildings were used to provide protection from the environment. This became necessary with humans moving into regions where the climatic conditions differed from the warm areas where they had originally emerged, along with changes to the physical appearance of humans, making it difficult or in most cases impossible to survive without some sort of protection. In the early stages, this protection was provided by nature in the form of caves, cliff overhangs and the like. Later, people started constructing their own protected areas in the form of buildings. These were still fairly primitive constructions.

After this initial phase a second period started, whereby in some cultures shelter was not necessarily the prime objective in a building design. In addition to protection from the environment, occupants asked for an internal environment which they perceived as pleasant and comfortable. One example is the underfloor heating systems used by the Romans (Figure 1.1), where heat was provided in a way that increased the comfort perception of the occupants [Lechner 2001]. Another example is cooling towers in arid regions (Figure 1.2) such as in North Africa [Lechner 2001] which generate, in combination with massive walls and small windows, a pleasant environment for the occupants.

However, over the years new inventions and technical developments again changed the way in which buildings were designed, removing more and more of the limitations previously imposed by nature. It is now possible to build in a hot, arid climate a building that despite fully glazed facades and high internal heat loads still provides acceptable thermal comfort conditions. Another example of how previous limitations were overcome are deep core buildings where rooms in the core location are lit by artificial light and ventilated by mechanical systems.

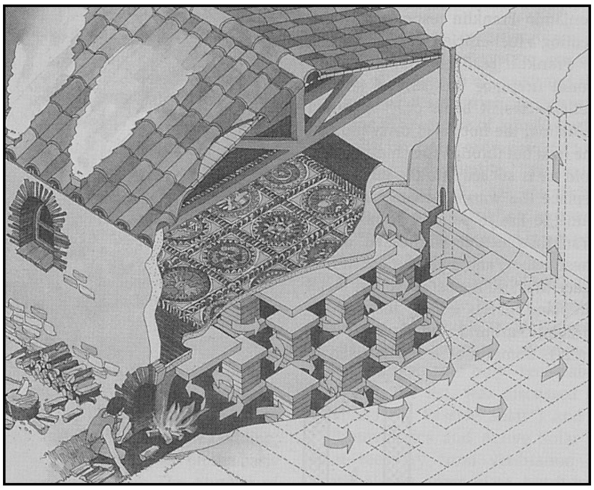

Figure 1.1: A Roman underfloor heating system (from [Lechner 2001])

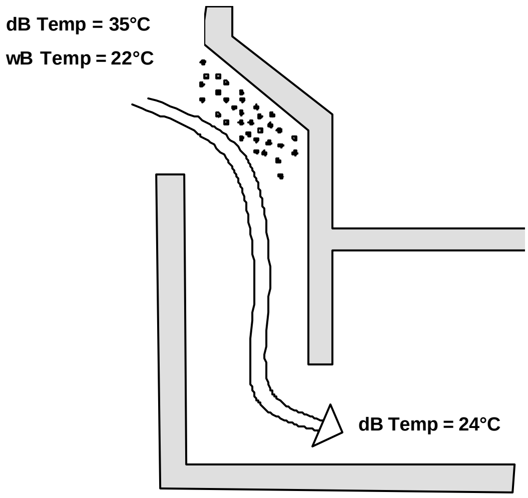

Figure 1.2: Principle of a cooling tower for hot and dry climatic conditions

Three main building services inventions can be identified as having enabled such design: (1) the invention of the light bulb, (2) mechanical ventilation systems and (3) chillers that can cool air or water. Another building services invention that relates not to the environmental control of a building but which moved the boundaries of building design was the development of lifts, enabling the easy transport of people and goods in high buildings. This, in combination with novel structural engineering methods (for example steel beams, reinforced or pre-stressed concrete) allowed the design of previously unknown building shapes.

All of this has led to the design of the buildings we live in today, and further changes can be envisaged in future. Brunel University [2000] has defined five waves of human technical development, the fifth wave being the information dissemination wave with inventions such as digital networks, software and new media (see Figure 1.3). These new inventions may well give raise to a new generation of buildings. Buildings could then be fully networked and hence controlled, operated and occupied in a manner different to current buildings. Research in this area is already underway [Clarke et al 2002, CIBSE 2002].

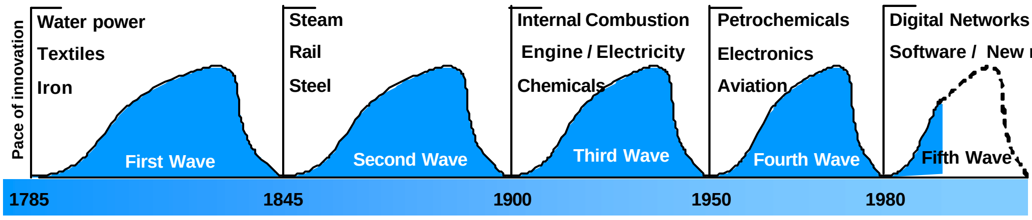

Figure 1.3: The five waves of human technical development (after [Brunel University 2000])

1.1.2 Quality of contemporary buildings

Despite the fact that a new generation of building(s) seems very likely, a common opinion is that contemporary buildings are often of poor quality. Sick building syndrome is an umbrella term for a number of phenomena that relate to buildings that provide an environment that is not pleasant, or that can even affect the health of the occupants. On a less dramatic scale it is not uncommon that occupants complain about poor ventilation, inappropriate heating control or overheating of spaces in summer [Jones 2001 b]. In this respect, it is often said that designers of pre-modern buildings were much more capable of ‘getting it right’ [Lechner 2001, Schneider 1996]. This is a view that will be investigated below in more detail.

1.1.3 Changes in the building design process

The changes of building design described in the previous section have also affected the building design process. Modern building design has moved away from a craft-based approach [Lawson 1990], where the building was the result of generations of evolution with an end product that is a totally integrated response to a limited number of problems (e.g. the climatic conditions in the location where the building is located). Lawson [1990] offers the examples of an igloo and a highland croft and points out that their design is a totally different proposition to the provision of housing in the noisy, congested city. He points out that

> *"the list of difficulties unknown to the builders of igloos or highland crofts is almost endless. Moreover each city centre site will provide a different combination of […] problems".*

An increased number of design difficulties is only one change in contemporary building design. The technical developments described at the beginning of this chapter give the designer a considerable number of options for tackling these problems. In addition, the modern building designer has to address legislative requirements, ranging from town planning to fire protection and energy conversation measures. Some of these legislative requirements are specified in the Building Regulations and will be discussed in the following section in more detail.

To support the designer in decision making in this complex and multi-objective planning process Design Decision Support Systems (DDSS) have been developed [Henrikson 2000] which the designer can apply if this is seen as necessary or relevant. These systems address aspects such as the cost of a building design or the design of the structural frame of the building. Some more novel examples are computer generated 3D animations of a building to give the designer and client a 'feel' for the design. Other systems address energy and environmental issues. The following section first discusses the concept of Building Regulations and then introduces different energy and environmental DDSS that can be utilised in the contemporary building design process.

1.2 Building Regulations

Building Regulations are produced by governmental bodies with the aim of ensuring that new building stock achieves a minimum energy (and nowadays also environmental) efficiency. They are the only energy and environmental considerations that (at least for new build design projects) the designer is obliged to address. Examples are the Building Regulations Part L for England and Wales (Part J for Scotland)[1] [DTLR 2002 a, DTLR 2002 b] and the German 'Wärmeschutzverordung' [WSchVO 1994].

In many western developed countries the first building regulations were originally developed in response to the energy crises of the early seventies [Oosterhuis and Nieuwlaar 1998, Gero et al 1983], as a result of which many Governments saw a need for the reduction of the energy consumption in the building stock. Initially these systems focused mainly on

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[1] Below only referred to as "Building Regulations".

the heating energy consumption of the building, with an emphasis on conductive heat loss through the building envelope. Later, they were expanded to also address phenomena such as plant efficiencies, ventilation heat loss and solar gains, and to consider other energy consumers in the built environment (cooling, lighting, mechanical ventilation).

This growth of aspects that are addressed in the Building Regulations facilitates a move towards an integrated design team where both the architects and building services engineers are encouraged to find an appropriate design solution for a particular project [Jones 2001 b]. The relevance of this development will be discussed later in more detail (section 1.6.4). After having given an introduction to Building Regulations in general the remainder of this section given an overview of the UK Building Regulations.

Currently (2002) the Building Regulations in the UK allow the designer to carry out an energy performance assessment in three different ways. The first (and simplest approach) is the *Elemental Method* where specific elements of the proposed building design have to fulfil certain criteria. The method includes maximum window sizes and insulation levels (U-values), requirements for plant efficiencies and specifications regarding the performance of the ventilation system. If a building does not pass the required standards based on the Elemental Method it is also possible to apply a trade-off between different design components, e.g. by showing that heat loss through a large window will be compensated by other, well insulated components of the building envelope[1].

If the Elemental Method still results in the building 'failing', it is possible to apply the *Whole-building Method* or *Carbon Emission Calculation Method* in which the building is assessed by simulating its performance in order to predict its carbon emissions[2]. The pass criterion for the Whole-building Method is that the carbon emissions of the complete building are not greater than maximum values specified for different building types. To show compliance with the Carbon Emission Calculation Method, the calculated annual carbon emissions for the proposed building should be no greater than those for a notional building of the same size and shape designed to comply with the Elemental Method.

The introduction of the Whole-building Method and Carbon Emission Calculation Method is a significant change in the way the Building Regulations address energy

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[1] This method does not have its own name, but is described as part of the Elemental Method under the section 'Trade-off between construction elements'.

[2] The Building Regulations do not specify which simulation tool or method to apply for the prediction of the building performance. Building control decides for each design project if the tool that was used is adequate. For this reason it is necessary to submit with every application for compliance under the Whole Building Method or Carbon Calculation Method a specification of the simulation tool that was used.

efficiency. A first significant difference is the fact that the methods remove the design restrictions that the Elemental Method imposes on the designer by specifying design parameters such as the construction used or window sizes. Secondly the methods embrace all the energy consumers in the building. This allows a trade-off approach between different energy consumers, hence further increasing the flexibility of the designer (e.g. lighting energy consumption vs. heating energy consumption). This trade of also includes an assessment of the energy type used (hence the use of electricity rather than gas as an energy source would be penalised).

1.3 Energy and environmental DDSS (EEDDSS)

There is a variety of energy and environmental DDSS (EEDDSS) available to the contemporary building designer. These range from design guidelines and rules to building simulation tools, which aim to predict the building performance of a certain architectural and/or engineering design proposal. The main groups are listed in Table 1.1 as a summary of descriptions and discussion which are included in the following sections (1.3.1 to 1.3.5).

EEDDSS	Description	Example
Design guidelines or rules of thumb	Do not predict performance but give general design advice.	BRECSU 77/98 software [BRECSU and Oscar Faber] Energy Efficiency Best Practice Programme [EEBPP 2002]
Traditional physical calculation methods (steady state)	Focus on a limited number of physical phenomena in a building, in some cases only on one.	JPA – Uvalue [JPA Designer 2002]
Correlation based methods	Try to consider all physical aspects that influence a certain building performance; restrictions in design specification and performance assessments.	BRE Environmental Design Guide for Naturally Ventilated and Daylit Offices [BRE 1998]
Building simulation	Philosophy of creating a virtual building where the user can specify in detail parameters that influence the building performance, with resulting performance predictions that are as close to reality as possible.	ESP-r [ESRU 2002] Radiance [Ward Larson and Shakespeare 1998]

Table 1.1: Different Energy and Environmental Design Decision Support Systems (EEDDSS)

1.3.1 Design guidelines or rules of thumb

Design guidelines or rules do not necessarily give any predictions about building performance. Rather they advise the designer what to do in order to achieve a certain performance target. An example is the material published by UK Government's Energy

Efficiency Best Practice Programme [EEBPP 2002], which provides designers with free publications on energy efficient building design[1]. Another example is the BRECSU 77/98 software [BRECSU and Oscar Faber], which gives guidance about appropriate cooling systems in a building.

1.3.2 Traditional physical calculation methods

EEDDSS that are based on traditional physical calculation methods aim to predict a certain physical process in a building, e.g. the conductive heat loss through the building envelope. The calculation can be carried out in the form of a hand calculation, but is nowadays often integrated into computer programs. An example is JPA – Uvalue [JPA Designer 2002], which calculates the U-Value of a construction depending on the materials used and their layer thicknesses. The software tool is also used in the architectural company were a large part of the research described in this thesis was carried out (section 1.7).

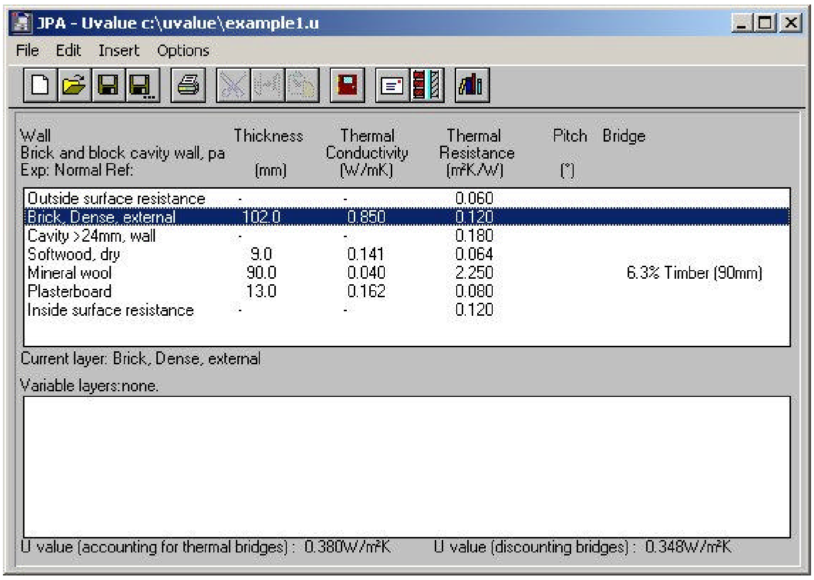

Figure 1.4: The JPA - UValue software for the calculation of U-Values

1.3.3 Correlation based methods

A limitation of traditional physical calculation methods is the restricted number of physical processes on which the results are based. However, buildings are very complex entities where numerous physical processes occur. Energy consumption is for example not

[1] The EEBPP is funded by the UK Department of the Environment, Food and Rural Affairs (DEFRA) and the Department of Transport, Local Government and Regions (DTLR).

only affected by conductive heat loss but also by ventilation heat loss, solar gains, etc. (see Figure 1.5 for an example of the processes that can occur). Correlation based methods have the aim of establishing predictions about the building performance taking these complex interactions into account. These correlations can for example be established by performing multiple parametric runs with advanced simulation programs. Often they work on the basis that the designer has to specify certain parameters and the tool then tells the designer how the building is likely to perform.

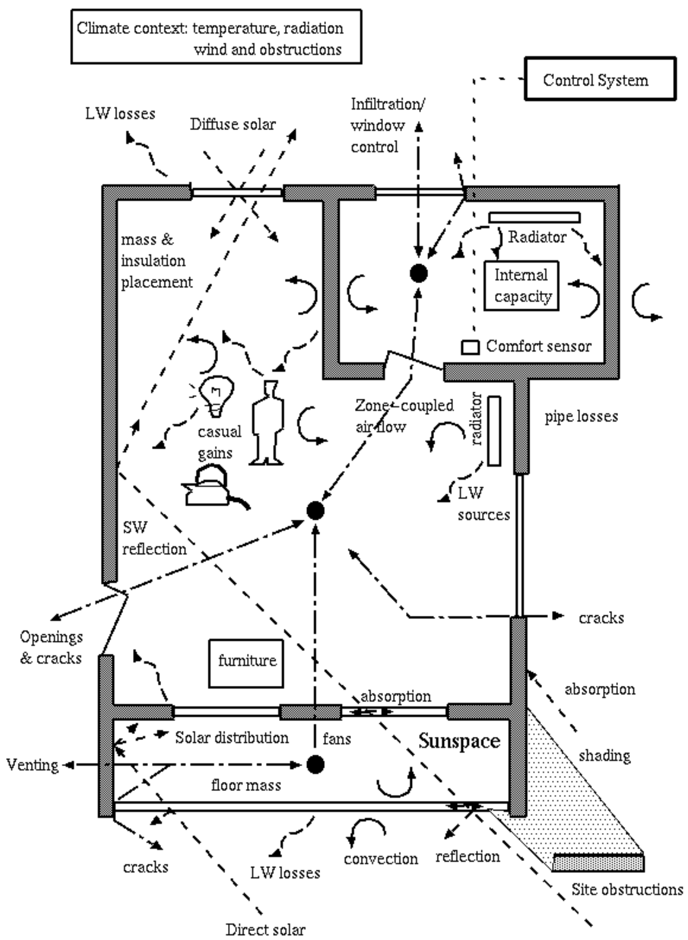

Figure 1.5: Energy flow paths in a building (from [Hand 1998])

An example for a correlation based EEDDSS is the Environmental Design Guide for Naturally Ventilated and Daylit Offices [BRE 1998]. This EEDDSS tells the designer for an office room what daylight availability and summer comfort conditions to expect. The assessment is based on the size and location of windows in the room, construction materials used, surface finish properties, internal heat loads in the building and shading from surrounding buildings as well as climatic conditions in which the building is located.

1.3.4 Building simulation

Building simulation expands the concept of performance prediction further. The philosophy of building simulation is to create a virtual building where the user can specify in detail parameters that influence the building performance[1], with resulting performance predictions that are as close to reality as possible. Some of the programs perform an assessment that also includes the dynamics of a building, e.g. dynamic thermal building simulation. Others only simulate a particular point in time, with Computational Fluid Dynamics (CFD) or lighting simulation programs being examples of this group. The former evaluates in detail the airflow in a space, the latter can be used to evaluate lighting levels and visual comfort conditions in a building. Some simulation tools also address several physical phenomena simultaneously and hence allow their combined assessment – previous methods only allowed them to be treated in isolation. An example of such a tool is the ESP-r system [ESRU 2002].

1.3.5 Small scale modelling

Another possibility is the evaluation of building performance by building and testing of small-scale models. These models can then be used for example to determine the pressure distribution around a building by carrying out wind tunnel tests or to evaluate daylight availability within a building. The results from tests can then also form part of the input data for a simulation model as pressure coefficient sets. The set-up for a wind tunnel test is displayed in Figure 1.6 and described in Etheridge and Sandberg [1996].

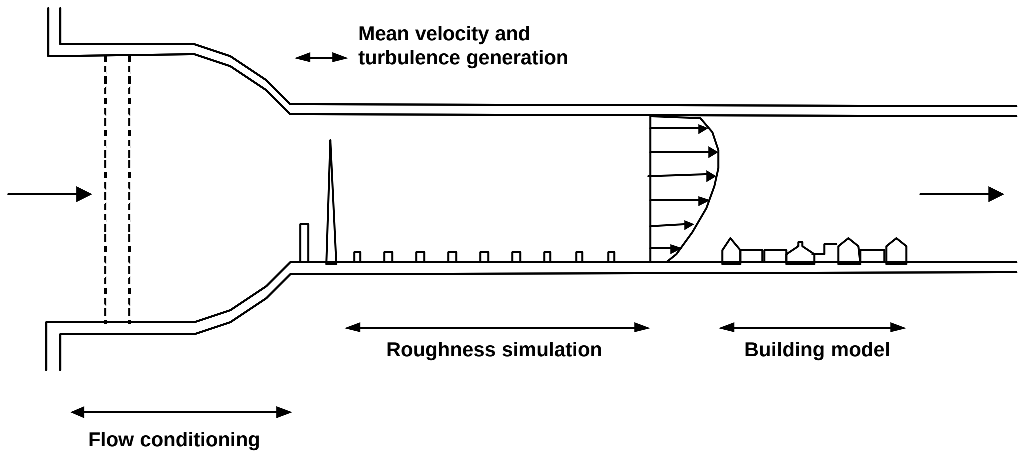

Figure 1.6: Setup for a wind tunnel test (after [Etheridge and Sandberg 1996])

[1] Altough the degree of detail again varies, as the following Chapter will show.

1.4 Discussion of Building Regulations and EEDDSS

Building energy consumption and indoor climate are determined by complex dynamic thermal interactions between the outdoor environment (air temperature, humidity, solar radiation, wind speed, wind direction), building structure, internal heat gains and the building services system, which performs heating, cooling, lighting and ventilation duties.

Simplified design tools such as design guidelines, rules of thumb, traditional physical calculation methods or correlation based methods have the limitation that the designer has to ensure that the design suggestions or performance predictions of these tools are appropriate for the building design where they are applied. Problems can occur if a specific design type was not accounted for when the simplified design tool was produced. Especially in cases of air flow assessments, small scale modelling has the disadvantage of being rather costly because a model of the building and its surrounding needs to be built and tested in a wind tunnel [Grant 2002].

All this leads Hensen [1994] to the conclusion that currently the most powerful technique available for the analysis and design performance assessment of complex building systems is building simulation because it takes into account all parameters that influence a building performance. He states that

> "*In the professional context, building energy simulation should be employed to make design decisions*".

Clarke [1997] points out that the advantage of the use of simulation lies in the fact that the tool

> "*permits an evaluation of building performance in a manner that corresponds to reality […] and enables integrated performance assessment in which no single issue is unduly prominent*".

Before expanding on the issue of how far simulation is currently being used in the building design process, another aspect will be discussed: to what extent do building designers address energy and environmental issues in the contemporary building design process?

1.5 Energy and environmental issues in the building design process

In the contemporary design process, not all design considerations are given the same priority. Some have to fulfil legal requirements (e.g. fire escape strategies), others are specified by clients (such as the budget for a project or expectations of the building functionality or aesthetics). The designer will normally give such issues a high priority when planning a building.

The literature lists numerous examples of how, by means of addressing energy and environmental issues, designers can realise buildings with very low energy consumptions or buildings with a comfortable internal environment (see for example case studies in [DETR] where buildings with a good energy and environmental performance are described). In the extreme this has resulted in designs like the "Energieautarkes Solarhaus" (Energy independent solar house), which has exceptionally low energy requirements and all demands are produced by the building itself [Schneider 1996]. Most energy and environmentally conscious buildings take this concept on board, however not to such a radical level.

Nevertheless, energy and environmental aspects do not yet find routinely attention in the contemporary building design process [Jones 2001 b, Lechner 2001, Schneider 1996, Gonzalo 1994]. Often, the only energy and environmental consideration made during a contemporary building design project is the evaluation of whether or not a building fulfils the requirements specified in the Building Regulations.

1.6 The application of simulation in the building design process

A large number of designers are involved in the design of a building - architects, building services engineers, structural engineers, etc. The implications of design decisions made by the different team members on the energy and environmental performance of the building differ, with architects and building services engineers having the biggest impact: architects because they deal with parameters that influence the energy and environmental performance of the building (material properties, glazing areas), and building services engineers because they design the systems that should later ensure a building provides appropriate environmental conditions. The following section discusses how far both groups currently apply building simulation as part of their decision making.

1.6.1 Architects

Mahdavi [1998] points out that modelling has a long tradition in the architectural design process, but that the main concern of architectural modelling has been visual appearance. He goes on and suggests that the increased complexity of building technologies has led to a broader view of architectural modelling which should cover aspects of buildings such as their performance in terms of energy consumption and thermal lighting and acoustic quality. However, simulation still finds only very limited application in the architectural design process. Robinson [1996] concludes from an extensive survey amongst practitioners that "there was a low take up of computerised energy calculations in the building industry, especially among architects". Such a conclusion can also be drawn when investigating the simulation capabilities that are available in a typical British architecture company, even among prestigious firms.

Another observation is that when simulation is applied, the exercise is seldom carried out by the architects themselves, but in the form of a subcontract to a simulation 'expert'. Funding schemes such as Energy Design Advice Scheme [McElroy et al 1997], where the clients obtain financial support for simulation based advice, have been catalysts for such simulation exercises.

1.6.2 Building Services Engineers

Simulation is currently more widely applied by building services engineers, with some engineering companies investing in in-house simulation capabilities (Cargill [2002] and Price [2000] both report deployment of simulation within engineering companies). Institutions such as the Charted Institution of Building Services Engineers (CIBSE) have begun to recognise the applicability of simulation and try to guide their members in the selection and use of such tools [CIBSE 1998]. However, among building services and environmental engineers simulation is not generally recognised as a DDSS [Bauer et al 1998, Andre and Nicolas 1994, Mahdavi 1998, Murray et al 2001]. This can also be seen by the fact that CIBSE still organises seminars that explain the general advantages and benefits of the application of building simulation in the design process, some of which are even targeted at young engineers who have only recently left University and hence are more likely to have been exposed to such tools [CIBSE 2001].

The following section discusses the issue that in cases were simulation is currently applied as part of the building design process the studies are often limited to the confirmation of the performance of a finalised building design. The then following section argues that generally the application of simulation in building design process is likely to increase in the future.

1.6.3 Performance confirmation versus design support

Rather than employing simulation early in the design process, a building designer will usually commission a simulation after finalising the design for performance verification [Hien et al 2000, Clarke 2000]. The fact that simulation is used for performance confirmation and not as a design support tool has two main implications:

- In the later stages of the building design process only a few design parameters are still flexible; hence the number of ways of resolving any highlighted problems are limited.
- If used late in the design process building simulation provides information at a design stage when it can make the least meaningful impact upon the quality of the building design. Using simulation at an early design stage could provide the designer with insight into the characteristics of a proposed building design at a time when it would be better utilised and therefore having a much more significant potential for the improvement of the building design.

Figure 1.7 illustrates the importance of informed design decision at early building design stages.

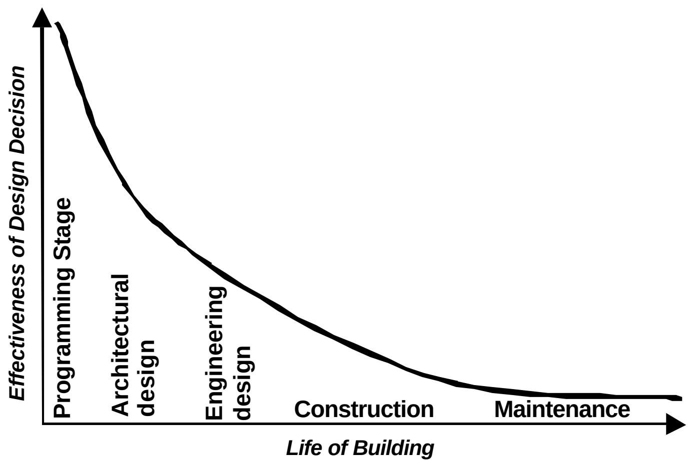

Figure 1.7: Relation between life of building and effectiveness of decision (after [Lechner 2001])[1]

1.6.4 The likelihood of change

It is likely that in future, energy and environmental issues will find increased consideration in the building design process. This could in turn lead to an increased use of simulation in the building design process. One catalyst that could trigger such a design approach is changes in the latest version of the Building Regulations. The existing Elemental

[1] [1] With 'Programming Stage' Lechner refers to the pre-design phase were the designer does not present design concepts to the client but tries to establish the boundary conditions within which to work (budgets, client expectations, design constraints). Actions taken by the designer during this period can still significantly influence in how far the final building design can potentially have a good energy and/or environmental performance. Examples are benefits from the designer using this period to explain to the client advantages of using simulation within the design process or promoting energy efficient design techniques like natural ventilation.

Method places such high emphasis on the insulation level of the building envelope [DTLR 2002 a, DTLR 2002 b] that design solutions such as façades with large glazing areas will in many cases not be able to gain approval on the basis of the Elemental Method. However, applying simulation in conjunction with the Carbon Emission Calculation Method or the Whole-building Method makes it possible to evaluate more accurately the implications of the large glazing areas on the energy consumption of the building. This, in combination with the fact that a simulation model can also include other energy conservation measures makes simulation a tool that will allow a more flexible design approach with respect to compliance under the new Building Regulations. The Carbon Emission Calculation Method and the Whole-building Method do not regard the insulation level of the façade (and hence the conductive heat loss through the building envelope) in isolation but evaluates the overall energy consumption of the building.

The introduction of a carbon emission tax [Environment Team, 2000] by the UK Government could also be seen as a driver for the use of simulation in the building design process [Jones 2001 a]. Since April 2002 the Government charges a tax of 0.43/0.15 Pence for each kWh of electricity/gas used. Although this relatively is rather minor, the effect will be more significant if the tax level applied reaches equivalent levels to the current tax on petrol (72.3% in 2000 [BBC 2002]). In such a scenario the energy consumption of the building would form a greater part of the life cycle cost of a building and in consequence the designer would give more attention to the expected energy consumption of a building design. Building simulation would then enable the design team to obtain a detailed understanding of how a particular building design performs, understand the reasons behind this performance and evaluate the effect of energy conservation measures.

Another incentive that can be identified for a potential growth in the use of simulation is the increase of privately financed public building projects (PFI/PPP) in recent times. In these schemes the investor who pays for the construction of a building is also responsible for its maintenance and running cost. This should increase the demand of such a client on the designer to consider the life cycle cost of a building during its planning phase. The energy consumption of the building forms a part of this overall life cycle cost. With building simulation it is possible to determine the energy cost that can be expected from a building design and also to determine in a comparative cost analysis the capital investment required for an energy conservation measure against the energy cost which it is going to save over the life span of the building.

1.7 Research aim and thesis structure

The above discussion has indicated that energy and environmental issues currently find only limited consideration in the contemporary building design process and that building simulation is a tool suitable to support the designer in addressing these design aspects. Simulation has to date found only limited application in the building design process, although reasons have been suggested as to why this situation could change in future.

These observations have prompted the development of the research aim: to moving building simulation towards an EEDDSS that is better integrated into the building design process. In order to pursue this aim, the following research objective is defined:

- Development of a methodology for the use of simulation within and throughout the design process.

Other objectives (which will be justified later in the thesis) are specified as follows:

- Specification and development of a tool that enables non-simulation experts to create a detailed simulation model at early building design stages (for justification see section 2.5.2).
- Specification of concepts and techniques for appropriate performance prediction analysis (for justification see section 2.5.4).
- Implementing and monitoring of the use of simulation at an early building design stage in an architectural design practice (for justification see section 3.3.1).

Figure 1.8 displays the structure of this thesis. Chapter 2 gives an overview of different types of building simulation programs that are available to building designers. Chapter 3 describes a methodology for the structured application of simulation in the building design process. This was developed to ensure that simulation is used effectively when it is applied throughout the design process. Chapter 4 describes an interface for a simulation program that aims to enable architects to carry out design evaluations by using simulation at early design stages. The objective behind this research was to move simulation from an engineering application to a tool that can be operated by architects. Chapter 5 then discusses developments to improve the analysis of performance predictions. The research in this chapter focused on architectural decision making as well as on later design stages where simulation is applied by engineers. Chapter 6 shows how research and developments introduced in chapters 3, 4 and 5 can be implemented in the building design process and also discusses practical implementation issues. Chapter 7 contains three case studies as well as feedback from designers regarding the benefits and implications of moving the application of simulation towards early building design stages and improving performance analysis methods. Chapter 8 concludes the thesis with a review of research contributions and suggestions for future research work.

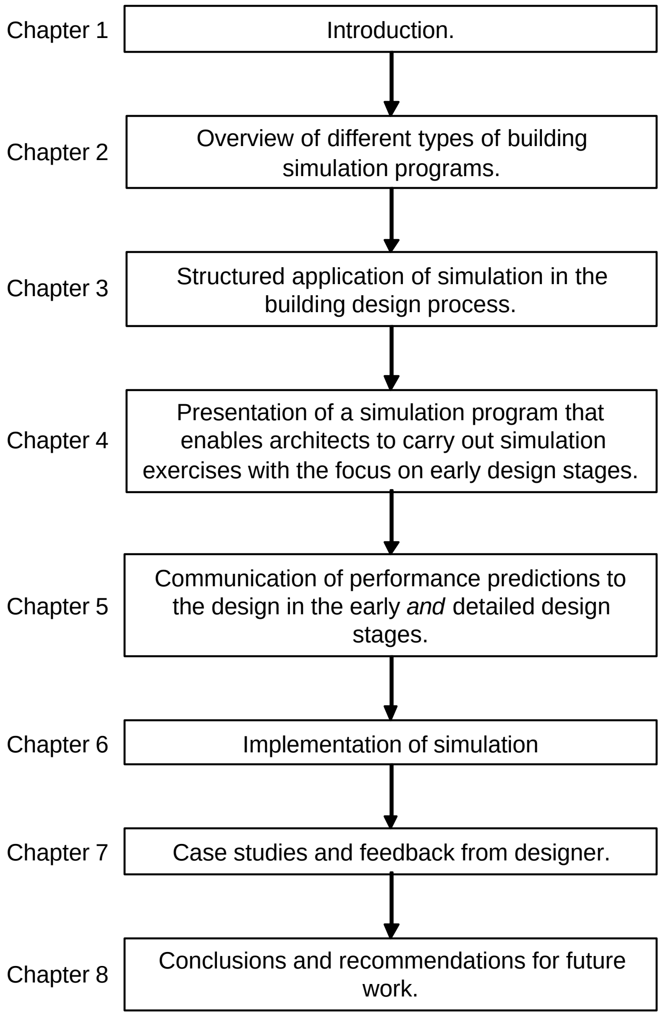

Figure 1.8: Thesis structure

The approach for the structured application of building simulation within the building design process described in chapter 3 covers thermal, lighting and air flow simulation. These simulation types have been the subject of much research and development and were also the focus of a design manual for simulation [CIBSE 1998], which gives a general overview of the application of building simulation. The research covered in chapter 3 was therefore carried out as broadly as possible so that the methodology developed could be applied to these main types of simulation programs. After chapter 3 the research concentrates on thermal and air flow simulation.

The author carried out the research for the structured application of simulation in the building design process in collaboration with design team members within an architecture company and was based during this time in their offices. The design practice has 160 members of staff, with four offices in different parts of Britain. The practice develops designs for different building types (e.g. commercial, health care, housing) with a large range of project values.

An architecture practice was seen as a good research environment as architects are generally seen as the “managers” of the design process, thus having a good general overview over the building design process. It was decided to focus the research only on one architecture practice, which has implications on the validity of the simulation approach because it raises the question in how far it is transferable to other design practices. However there were significant advantages in this approach: it enabled a detailed, focused study of how to best incorporate simulation into the design process and it provided an ideal testbed for testing software prototypes. Also design team members had experience of work practices in other companies and could hence put the issues regarding the use of simulation within the design practice in a wider context which was not only limited to the one company.

References

Andre P, Nicolas J, “Use of an Integrated Software System for Building Design and System Simulation”, Proceedings of the Conference of Systems Simulation in Buildings, Liege, Belgium, 1994.

Bauer M, Haller R, Sucic D, “OPTIMO – A Software Tool Generating Building Models for Simulation Programs from CAD Drawings”, Proceedings of the Conference of Systems Simulation in Buildings, Liege, Belgium, 1998.

BBC, “UK Fuel Tax: The Facts”, http://news.bbc.co.uk/1/hi/in_depth/world/2000/world_fuel_crisis/933648.stm, 2002.

BRE (Building Research Establishment), “Environmental Design Guide for Naturally Ventilated and Daylit Offices”, BRE Publication, 1998.

BRECSU and Oscar Faber, “BRECSU 77/98”, Software for the Evaluation of Alternative Cooling Systems.

Brunel University, “Exploring Design and Innovation – Fresh Ideas for Creative Curriculum Development”, Published by the Department of Design at the Brunel University with Support from the Design Council, 2000.

Cargill R, Building Services Engineer at FaberMaunsell, Personal Communication, 2002.

CIBSE, “Building Energy and Environmental Modelling”, CIBSE Application Manual AM 11, CIBSE, 1998.

CIBSE, “Building Simulation”, Young Engineers Meeting, Glasgow, 2001.

CIBSE, “Intelligent Buildings”, Building Services Journal, June Edition, pp 37-53, 2002.

Clarke J A, “Building Performance Simulation Using the ESP-r System”, Proceedings Building Simulation 97, Prague 1997.

Clarke J A, Johnstone C M, Kim J and Strachan P A, “On-line Energy Services for Smart Homes”, 3rd European Conference on Energy Performance and Indoor Climate in Buildings (EPIC 2002 AIVC), Lyon, France, 2002.

Clarke J A, Personal Communication 2000.

DTLR a (Department of Transport, Local Government, Regions), “The Building Regulations 2000, Part L1”, 2002.

DTLR b (Department of Transport, Local Government, Regions), “The Building Regulations 2000, Part L2”, 2002.

DETR (Department of Environment, Transport and the Regions), “Good Practice Case Studies Series”, several publication issued over several years.

EEBPP (Energy Efficiency Best Practice Programme), “Homepage of the UK Government’s Energy Efficiency Program for the Built Environment”, http://www.energy-efficiency.gov.uk/, 2002.

Environment Team, “UK Environmental Headlines”, Published by the British Embassy in Berlin, 2000.

ESRU (Energy Systems Research Unit), “ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series”, University of Strathclyde, Glasgow, 2002.

Etheridge D, Sandberg M, “Building Ventilation – Theory and Meassurement”, John Wiley and Sons, 1996.

Gero J S, D’Cruz, Radford A D, “Energy in Context: A Multicriteria Model for Building Design”, Building and Environment, Volume 18, No 3, pp 99-107, 1983.

Gonzalo R, “Energiebewusst Bauen”, Edition Erasmus, 1994.

Grant A, “The Use of CFD Simulation in Building Design”, Seminar by the Scottish Energy Systems Group, 2002.

Hand J W, “Removing Barriers to the Use of Simulation in the Building Design Professions”, PhD Thesis University of Strathclyde, 1998.

Henrikson C, “The Bigger View - Optimising Solar Energy Use in Large Buildings”, Renewable Energy World, Vol. 3, No. 3, 2000.

Hensen J L M, “Energy Related Design Decisions Deserve Simulation Approach”, Proceedings of the International Conference on Design and Decision Support Systems in Architecture & Urban Planning, Vaals, 1994.

Hien W N, Poh L K, Feriadi H, “The Use of Performance-based Simulation Tools for Building Design and Evaluation – a Singapore Perspective”, Building and Environment, Volume 35, pp 709-736, 2000.

Jones P a, “Energy Efficient Heating Systems”, CPD Seminar Organised by the Chartered Institution of Building Services Engineers (CIBSE), London, 2001.

Jones P b, “Energy in Buildings”, Workshop organised by the Chartered Institution of Building Services Engineers (CIBSE), Manchester, 2001.

JPA Designer, “JPA Designer Homepage”, www.techlit.co.uk, 2002.

Lawson B, “How Designers Think – The Design Process Demystified”, Butterworth Architecture, 1990.

Lechner N, “Heating, Cooling, Lighting – Design Methods for Architects”, John Wiley and Sons, 2001.

Mahdavi A, “Computational Decision Support and the Building Delivery Process: a Necessary Dialogue”, Automation in Construction, Vol. 7, pp 205-211, 1998.

McElroy L B, Hand J W, Strachan P A, “Experience from a Design Advice Service Using Simulation”, Proceedings Building Simulation 97, Prague 1997.

Murray V, O’Flynn C J, Beattie K, “Advanced Building Services Simulation Software Providing Design Solutions in Dublin and Boston”, Proceedings Building Simulation 01, Rio de Janeiro 2001.

Oosterhuis F, Nieuwlaar E, “Efficiency Policy Instruments for Energy Efficiency in Residential Space Heating – an International Empirical Analysis”, Working document by Utrecht University, 1998.

Price D, Head of Simulation Unit at Whitby and Bird, Personal Communication, 2000;

Robinson D, “Energy Model Usage in Building Design: a Qualitative Assessment”, Building Services Engineering Research and Technology, Vol. 17, No. 2, CIBSE, pp 89-95, 1996.

Schneider A, “Solararchitektur für Europa”, Birkhäuser Verlag, 1996.

Ward Larson G, Shakespeare R, “Rendering with Radiance: the Art and Science of Lighting Visualisation”, Morgan Kaufmann, 1998.

WschVO (Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden - Wärmeschutzverordnung), Bundesgesetzblatt I, 1994.

CHAPTER 2

BUILDING SIMULATION TOOLS

2.1 Introduction

Chapter 1 described how the complexity of the building design process has led to the development of DDSS. The chapter also identified dynamic building simulation as a potentially powerful design support system to address energy and environmental aspects of building design.

This chapter firstly provides an overview of dynamic building simulation. This includes a description of the evolution of simulation over previous decades, the simulation capabilities that are currently available and a discussion of the current state of coupling of simulation to the building design process. It then discusses different means of performance communication, ranging from display types which are already routinely applied to research applications of visual display. The following sections contain a comparison of different simulation tools and barriers to the application of simulation in the building design process.

2.2 Overview of building simulation

2.2.1 Evolution

Until the mid 1970s, simplified calculations were used to estimate the energy usage in buildings [Clarke 2001]. They reduced the complexity of the system to be emulated (a whole or part of a building) by simplifying parts of this system (e.g. solar heat gains or long wave radiation exchange between surfaces) and imposing simplified boundary conditions (e.g. constant temperature differences). Such methods still find application in the building design process, as stated in the previous chapter.

Building simulation aims to imitate the real physical conditions in a building by creating a mathematical model that (ideally) represents all energy flow paths in a building as well as their interactions. Advances in simulation techniques and computing facilities have led to the development of very advanced building simulation tools. Clarke [2001] has summarised this evolution from tools that are based on traditional calculation methods to contemporary simulation over four generations as outlined below.

1^st^ Generation: Such tools are handbook orientated computer implementations and are biased towards simplicity. There is no attempt to faithfully represent the energy and mass flow paths that occur in a real building but the aim is to provide the user with general indications of certain building performance criteria.

2nd Generation: In the mid-seventies 2nd generation tools emerged. They introduced the dynamics of a building in the evaluation process in an attempt to imitate the real physical conditions in a building, particularly with respect to long term constant elements such as multilayered constructions, but the analysis was still decoupled in relation to treatment of air movement or HVAC systems. Early implementations were not applicable for the design process due to limited interfaces and computational requirements [Hand 1998].

3rd Generation: With advanced and more powerful personal computing facilities, 3rd generation programs began to emerge in the mid-eighties. These assume that only space and time are independent variables; all other system parameters are dependent so that no single energy or mass transfer process can be solved in isolation. An example of a 3rd generation tool is the coupling of an air flow network model with a thermal model in order to perform a combined assessment of energy and mass flow [Hensen 1991].

4th Generation: 4th generation program development started in the mid-nineties. This involved further domain integration (see [Negrao 1995] or [Kelly 1998] for examples), but also considered program interoperability, which is essentially a data modelling issue (as achieved by [Janak 1998]). In response to the growing uptake by practitioners, new developments emerged, including more accessible user interfaces, application quality control [Hand 1998, Cooper at el 2000] and user training [CIBSE 1998, Hand and Hensen 1995, Hand 1993]. Air flow simulation is well integrated in 4th generation tools [ESRU 2002, Dorer et al 2001, Crawley et al 2001] and is also commonly applied in the building design process (both Ho [1999] and Hand [2000] are both experienced simulation consultants who observed this pattern].

The above section describes the development from traditional assessment methods to contemporary simulation software[1]. Clarke states that 1st generation tools are easy to use but difficult to translate to the real world and with hidden deficiencies. Going through the different generations, their evaluation is based on data closer to the real world. In the case of 2nd and 3rd generation programs, however, this is often at the expense of a complex software structure. In 4th generation programs, the in-built assumptions should be made explicit, they should undertake multi-variant analysis and they should be easy to use and interpret. Figure 2.1 depicts this process.

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[1] It is not clearly defined when to start referring to 'simulation tools'. Hand (1998) describes 2nd generation tools as simplified methods, whereas Beausoleil-Morrison (2000) refers to them as simulation programs.

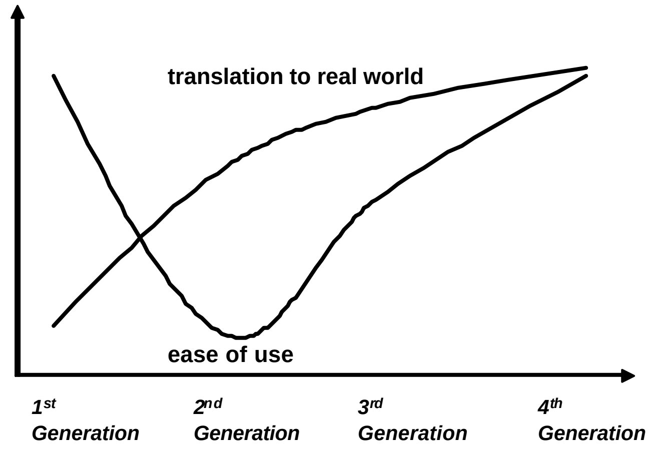


Figure 2.1: Translation to real world and ease of use in simulation

However, the development of 4th generation simulation tools is not complete. This is an issue that will be discussed in more detail later in this thesis (section 2.5.3, 2.5.4). As a consequence, users with limited background in energy and environmental aspects of building design might turn towards simplified early generation tools, where they feel more competent in operating the system. Implications of such a choice will be discussed later in more detail (section 2.4).

2.2.2 Simulation capabilities

The previous section describes the evolution of dynamic building simulation towards an EEDDSS that will allow a holistic appraisal of a building design. This section gives a brief overview of the different types of simulation appraisal that can be carried out by a designer with an advanced simulation program. It is based on experience of the ESP-r system [ESRU 2002], the development of which began over 25 years ago [Clarke 1977] and which has been under continuous evolution ever since.

The bases of each simulation model are polyhedral zones (see Figure 2.2) that are attributed with construction, internal heat gain and idealised ventilation and infiltration data. It is then possible to add extra model components for a more detailed definition of the design in the simulation model (see Table 2.1).

From table 2.1 it can be seen that valuable information can already be gained from a simple attributed polyhedral zones (overheating assessment, visualisation analysis, etc.), but the table also shows benefits from the integration of additional components if the design process requires more detailed results (e.g. an air flow network rather than idealised ventilation and infiltration). The skills required for various simulation assessments differ –

including a solar obstruction element into a thermal model is relatively straightforward, whereas extending the model to also carry out a CFD analysis is more complex and requires from the user an understanding of the physical processes that are to be simulated.

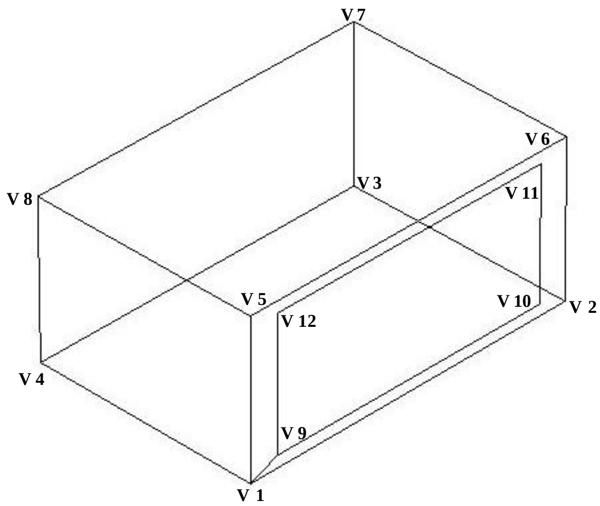


Figure 2.2: One zone of a simulation model (including vertices)

Model components	Design assessment enabled
The basic model: building geometry, construction, climate, internal heat gain and idealised ventilation and infiltration attribution.	Overheating and summer comfort assessment (including evaluation of impact of mass), visualisation, embodied energy, acoustics and daylight factors within the building, visual comfort and glare studies.
Inclusion of zone based control.	Evaluation of heating and cooling control strategies, energy requirements, system response, determining of required plant sizes, heated construction models (e.g. under floor heating), daylight utilisation.
Shading and insulation, blinds, blind control.	Solar control strategies, shading from surroundings and self-shading.
Air flow network.	Evaluation of natural or fan assisted ventilation systems, more realistic summer comfort and passive cooling system studies.
HVA C networks.	System simulation, component sizing.
CFD.	Natural or fan assisted ventilation system simulation studies within a room, convective heat transfer calculations, indoor air quality studies.
Special materials.	Photovoltaic and advanced glazing studies.
Electrical power networks.	Building integrated generation systems, renewable energy integration, demand and supply matching.
Moisture networks.	Condensation analysis, prediction of mould growth, evaluation of health hazards in the built environment.

Table 2.1: Different components in a simulation program (based on [Clarke 2001] and [Kelly 1998])

2.2.3 Coupling of simulation to the building design process

The application of simulation programs within the design process can vary from a routine evaluation by designers who make decisions that influence performance (e.g. an architect who evaluates implications of different window sizes) to a specialist who has been instructed by the design team to evaluate a certain design aspect. McElroy and Clarke [1999] have described the difference diagrammatically as shown in Figure 2.3 and referred to this as de-coupled and integrated simulation application. Efforts to enhance the general application of simulation should also encourage its integrated application. Benefits of the approach will be outlined later in this thesis (section 3.6).

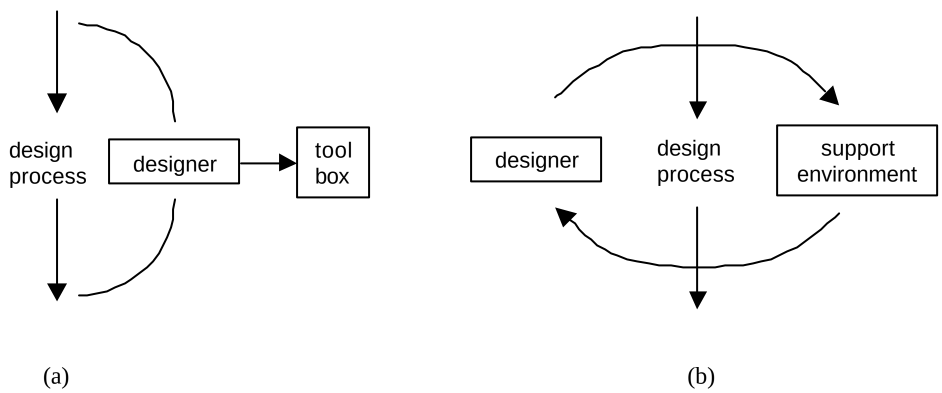


Figure 2.3: Simulation (a) de-coupled from the design process and (b) as an integrated application (after [McElroy and Clarke 1999])

2.3 Performance communication

After the creation and simulation of a model the next task is the analysis of the performance predictions by relevant parties. This could either be a designer carrying out the simulation exercise, a designer who uses the performance predictions during the design decision making process or a client to whom the outcome of a simulation exercise is presented. The main thrust of research into performance prediction analysis as described in this thesis is to enable *designers* to understand the outcome of simulation exercises, but section 5.3.1 will also expand in more detail on how likely it is that clients view at the different building design stages simulation performance predictions.

This section describes different means of communicating performance predictions, which form an important part of the performance prediction analysis.

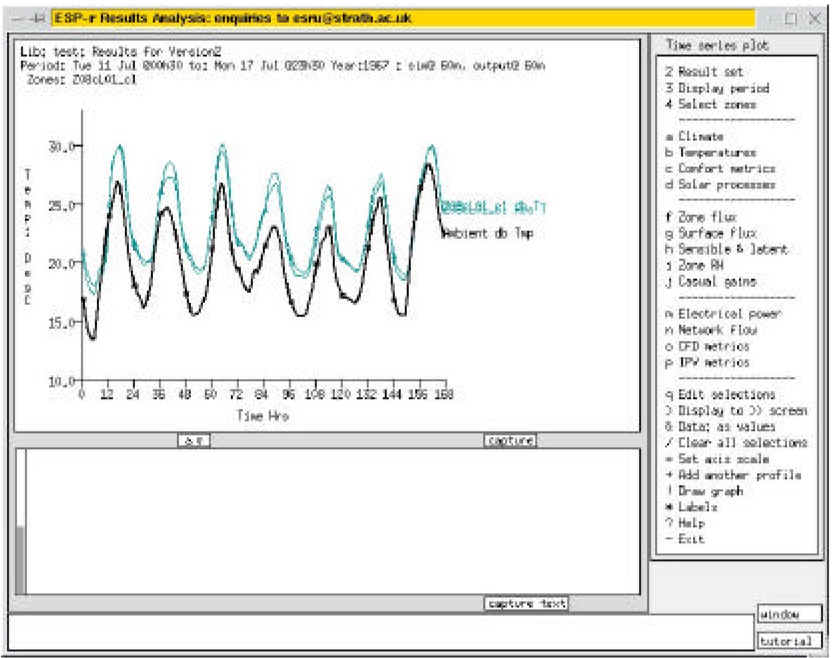
2.3.1 Performance prediction domains

Early developments of dynamic thermal building simulation only provided performance predictions that relate to thermal aspects of the building design (e.g. room temperature, heating or cooling predictions). However, with the integration of additional, non - thermal capabilities in 3rd and 4th generation simulation programs, the information that can be obtained from a simulation has been significantly increased.

Timestep performance metrics.
Lib: ref1-opt4_1.res: Results for ref1-opt4
Period: Sat 4 Jan @00h30 to: Mon 31 Mar @23h30 Year:1997 : sim@ 60m, output@ 60m

Time	Dir Norm solar W/m^2	Ambient db Tmp deg C	ps_rec_grd HeatInj kW	ps_con_grd HeatInj kW	pv_con_1+2 HeatInj kW	pv_con_3+4 HeatInj kW	ps_rec_grd Res T deg C	ps_con_grd Res T deg C	pv_con_1+2 Res T deg C	pv_con_3+4 Res T deg C
00h30	0.00	0.25	20.74	21.13	8.42	10.81	16.98	14.81	14.33	13.58
01h30	0.00	0.00	20.74	19.36	9.70	11.81	17.33	14.73	14.17	13.42
02h30	0.00	-0.05	20.31	19.31	9.93	11.92	17.53	14.74	14.14	13.39
03h30	0.00	-0.30	9.07	18.57	10.96	11.92	17.62	14.62	13.98	13.14
04h30	0.00	-0.75	20.74	26.04	11.85	11.92	17.18	14.42	13.79	12.87
05h30	0.00	-1.10	20.74	24.93	11.92	11.92	17.40	14.40	13.74	12.77
06h30	0.00	-0.75	20.74	24.22	11.92	11.92	17.50	14.43	13.72	12.75
07h30	0.00	-0.40	15.99	21.52	11.02	11.92	17.75	14.63	13.95	13.01
08h30	0.00	-0.25	11.67	17.61	9.57	11.89	17.83	14.81	14.13	13.28
09h30	6.50	0.25	20.74	21.06	9.11	11.38	17.58	14.85	14.21	13.40
10h30	13.00	0.95	6.48	13.61	7.62	9.82	18.10	15.11	14.47	13.74
11h30	6.50	1.55	2.59	13.20	6.37	8.46	18.04	15.27	14.74	14.08
12h30	0.00	1.80	0.00	13.17	6.21	8.21	18.04	15.28	14.80	14.17
13h30	8.00	2.10	0.00	13.70	6.15	8.05	17.90	15.25	14.82	14.20
14h30	16.50	2.45	0.00	12.36	6.01	7.83	17.60	15.24	14.83	14.24
15h30	9.00	2.15	0.00	12.66	6.70	8.57	17.19	15.09	14.69	14.07
16h30	0.50	1.80	14.26	15.34	8.69	10.67	16.72	14.72	14.29	13.56
17h30	0.00	2.00	10.80	14.89	8.87	10.85	16.88	14.69	14.23	13.48
18h30	0.00	2.20	0.00	12.99	8.48	10.52	17.06	14.75	14.30	13.56
19h30	0.00	2.30	0.00	13.59	8.32	10.27	16.77	14.73	14.31	13.60
20h30	0.00	2.10	0.00	13.68	8.25	10.14	16.62	14.70	14.31	13.62
21h30	0.00	1.55	0.00	14.72	8.33	10.19	16.44	14.66	14.29	13.63
22h30	0.00	0.90	0.00	15.96	8.63	10.44	16.28	14.59	14.22	13.54
23h30	0.00	0.60	0.00	16.06	8.92	10.72	16.21	14.50	14.15	13.45
00h30	0.00	0.55	15.99	20.54	9.21	10.81	15.80	14.42	14.07	13.36
01h30	0.00	0.40	20.74	23.38	9.47	11.28	15.91	14.41	14.02	13.32

(a)



(b)

Figure 2.4: Different output types: (a) tabular (b) graphical

2.3.2 Data display types

Dynamic thermal simulation programs produce at every time step a set of performance predictions. There are different ways in which this data can be processed and displayed to the user. The CIBSE Application Manual 11 [CIBSE 1998] distinguishes digital, tabular and graphical display. Digital output is very cumbersome to investigate and is normally not applied in the analysis process. Tabular and graphical display find wider application. Figure 2.4 gives an example for each type.

Figure 2.5 shows that performance communication methods can be further differentiated (a more detailed discussion of the different performance communication methods is summarised in sections 2.3.3 to 2.3.7). Generally it can be observed from the diagram that tabular data can be further processed into summary data and that (in a more recent development) integrated performance displays have been introduced to support a more holistic analysis of the building behaviour (the concepts of integrated performance displays will be described in discussed in section 2.3.6). Additional research is also carried out within the building simulation community into more innovative concepts of graphical display and will be introduced later in this chapter in section 2.3.7.

2.3.3 Tabular display

Tabular display is mainly applicable if different data entities in one time step need to be compared (e.g. indoor temperatures at the beginning of occupancy periods on a cold winter day).

2.3.4 Summary data

Summary data can be produced by adding the hourly data produced in tabular form for example when predicting the heating energy consumption over the entire simulation period or when extracting maximum values to determine plant capacities or peak temperatures in a zone. Filters can enhance this analysis process. An example of this is the case when the user wants to determine the hours that the temperature in a zone will exceed a certain temperature. Multiple filters can further enhance the information value, for example when carrying out the same exercise but only during occupied hours.

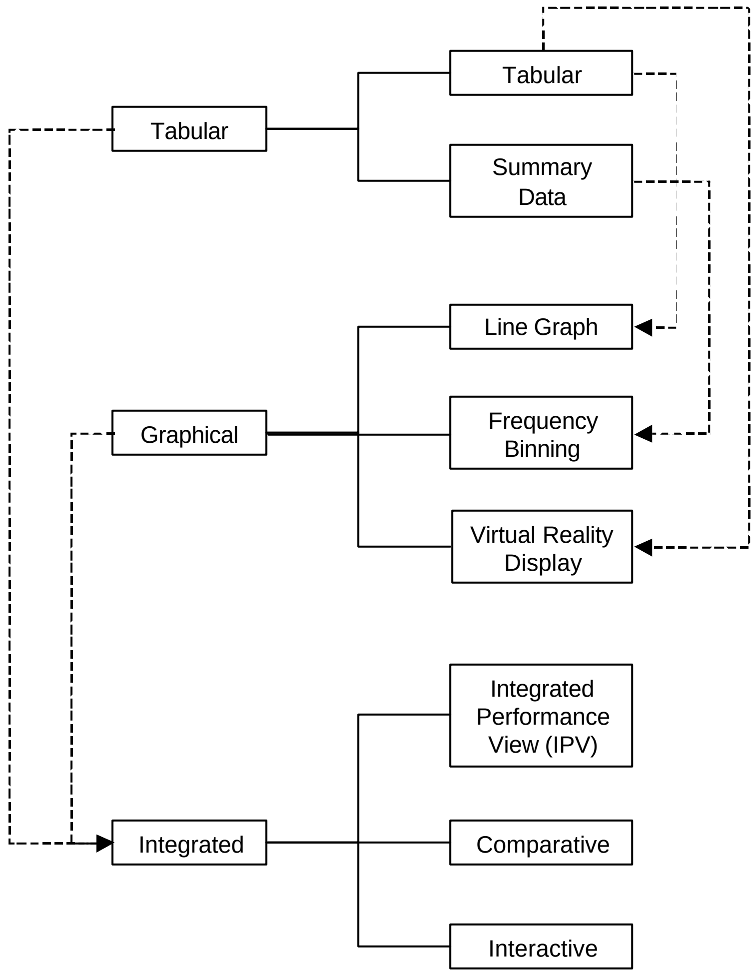


Figure 2.5: Different performance communication methods

2.3.5 Graphical analysis

Although it is possible to analyse time series data in tabular form this often gives only limited insight into the behaviour of the building. Graphs can be more suitable for this analysis. Consequently, modern simulation programs normally present performance predictions in graphical form [ESRU 2002], or at least provide facilities that will allow the quick export of this data into a spreadsheet where it can be analysed [Crawley 2001].

Graphical display can vary from line graphs and bar charts to pie, scatter or radar charts. Tufte [1983] gives a comprehensive overview of issues related to the graphical display of information. The main display types found in contemporary building simulation tools are line graphs and frequency binning, the latter mainly displaying summary data.

2.3.6 Integrated performance display

Traditionally, the gathering of performance data has been left to the user of the simulation program. Apart from the fact that this process can be tedious and time consuming, it also bears the risk that the user does not consider all of the relevant performance parameters that could be obtained from the simulation exercise. To address both of these issues ESRU [Clarke et al 1998] has developed Integrated Performance Views (IPVs), which are created automatically by the ESP-r simulation software.

Figure 2.6 shows an IPV for the Brundtland Centre in Denmark. Taking each portion of the IPV in turn, the topmost left indicates the design variant and its features. The three graphs across the top deal with capacities and thermal and visual comfort in different areas of the building. The middle row addresses emission figures, daylight availability as well as glare. The bottom row shows typical demand profiles at different times of the year and also provides figures that indicate the annual energy consumption of the building.

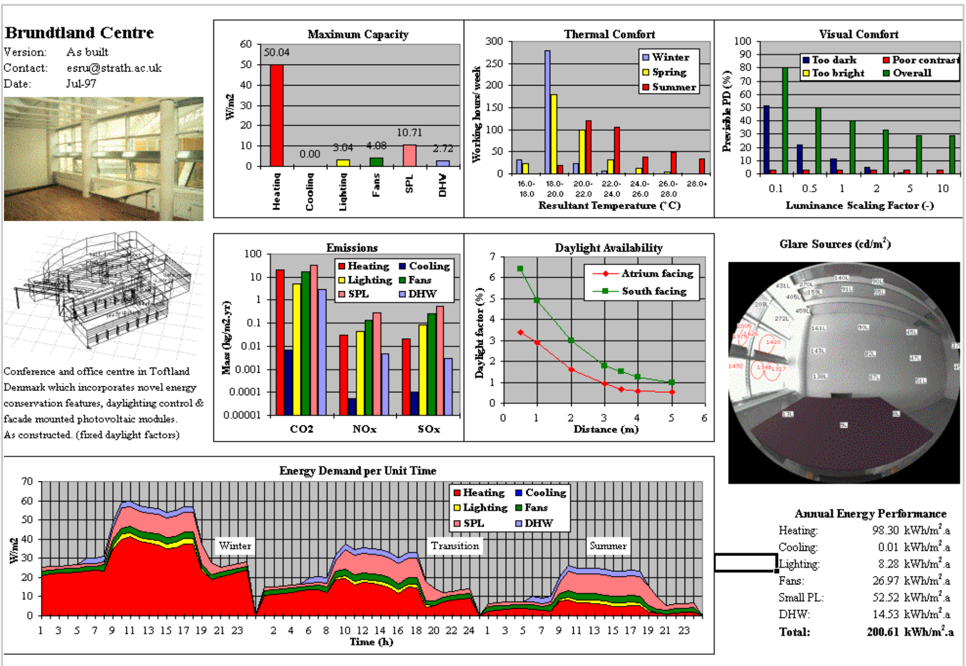


Figure 2.6: An Integrated Performance View (IPV)

The development of IPVs has enhanced performance communication to the viewer. Their quick and easy generation and standardised output format makes them especially suitable for communication to non-simulation experts who want to obtain an understanding of the general performance of the design that has been simulated. A user can also generate a number of IPVs and compare the performances of the different design versions they represent.

Both the Glazing System Design Tool [LESO-PB 1998] and the Building Design Advisor (BDA) [LBNL 2002] have further enhanced integrated analysis by introducing interactive analysis tools. Rather than having a static display these tools allow the designer to focus on certain aspects of the building performance and also permit comparative analysis of different simulation models. Figure 2.7 show the BDA Decision Desktop, displaying the performance of different models.

2.3.7 Research applications of visual display

The communication methods that have been described so far are already used to provide performance predictions to either the user of the software or the designer. However, recent research has been carried out into alternative ways of presenting this information. Research into the export of simulation results into a virtual reality world is one example.

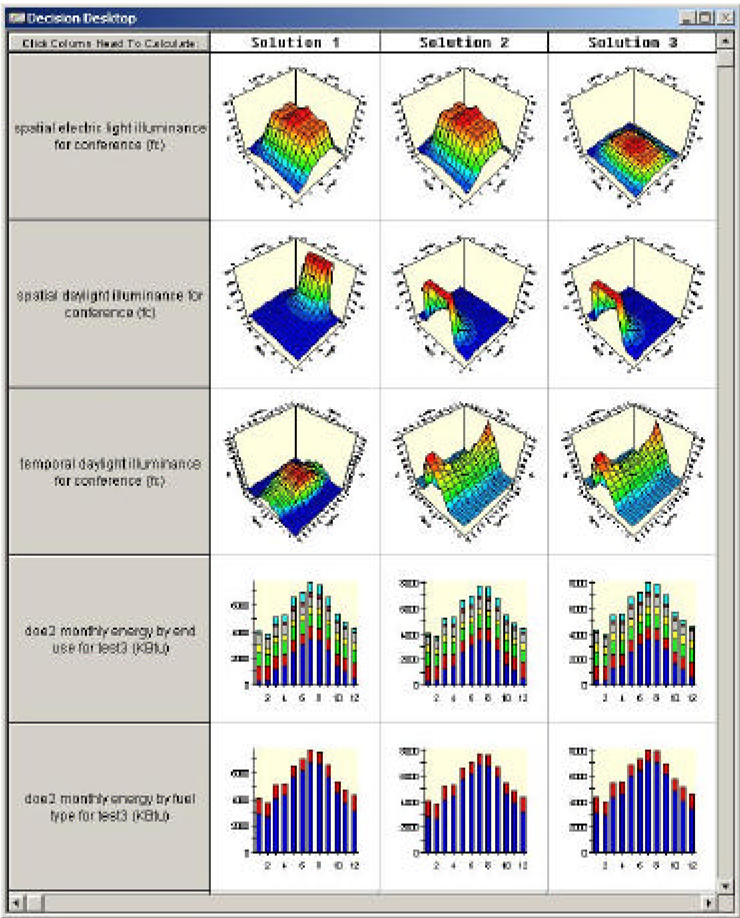


Figure 2.7: The BDA Decision Desktop

A common definition for virtual reality has not yet been established [Kühner 1999]. Some definitions refer to the visual display of complex and large data sets, others emphasise a 3D display or interactive user functionalities.

An example for an interactive interrogation of lighting predictions is provided in [Glaser and Ubbelohde 2001], whereby it is possible to focus the analysis on certain spaces in a room and/or on specific time periods of the year. However, the program has only a 2D display of the results, hence the 3D aspect is not considered. Figure 2.8 shows a result display example.

Fundamental limitations still exist for the application of virtual reality software that allows 3D display and interactive data interrogation in the design process. Glaser [2001] for example points out that the generation of the data required for his performance display was very time consuming. Another issue is that necessary links for data exchange between different software tools are often as yet inadequately developed [Van Leeuwen 2001].

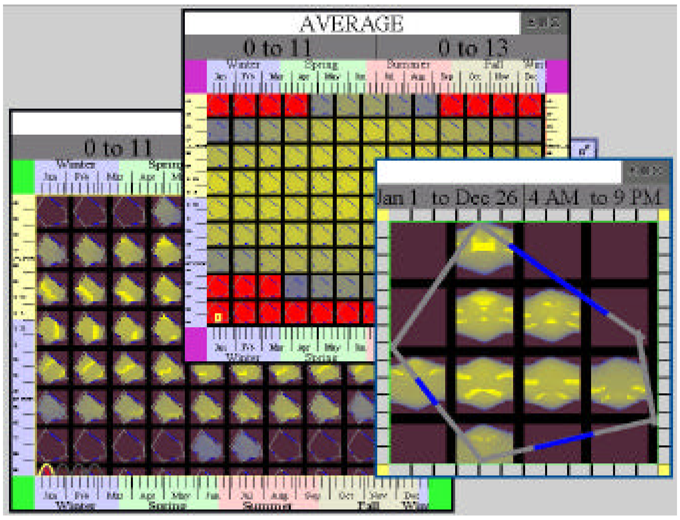


Figure 2.8: Visualisation of lighting simulation results (from [Glaser 2002])

2.4 Comparison of different simulation tools

After having raised the issue of the evolution of building simulation and aspects related to the communication of performance predictions to the designer, this section gives an overview of different simulation programs. It gives insight into what software types are currently available to designers and discusses the adequacy of the tools for application within the building design process.

2.4.1 Selected simulation tools

A large number of simulation tools have been developed over the last few decades. The building energy software tool webpage [DOE 2002] run by the US Department of Energy lists over 240 tools, ranging from research grade software to commercial products. Testing and ranking all of these tools was not possible within the scope of this research, but an attempt was made to evaluate representative programs. Four different software tools were selected:

- ESP-r [ESRU 2002]
- LT-Method [Baker and Steemers]
- Energy 10 [NREL 2002]
- Building Design Advisor (BDA) [LBNL 2002]

ESP-r was chosen because it is a software tool that aims to predict building performance with a simulation model that closely represents the conditions that occur in reality. The LT-Method was selected because it puts the emphasis on quick model definition and fast performance evaluation for comparative studies rather than model accuracy. Robinson [1996] illustrates the differences in the approaches by categorising simulation tools on a scale depending on their model accuracy. The LT-Method and ESP-r are located at either end of this scale (see Figure 2.9).

1	2	3	4	5	6	7	8	9	10
LT-Method	Anglia Daylight	Esi-Check	NHER/ BREDEM	QUICK/ NORMA	HEVA-COMP	Facet APACHE	SERI-RES	Tas	ESP-r

Figure 2.9: Categorisation of simulation programs (after [Robinson 1996]) (1-4 simple, 8-10 detailed, 5-7 transitionary)

Both Energy 10 and the BDA have been selected because they have been developed with the specific aim of creating simulation programs that make it easier for designers to carry out a simulation exercise. Both tools have again followed different philosophies: Energy 10 focuses on simple and quick model definition whereas BDA puts the emphasis on accurate model definition.

ESP-r: ESP-r has been developed by the University of Strathclyde in Glasgow, UK. Initially only a dynamic thermal simulation software it has been expanded over the last two decades to a simulation package with several additional simulation capabilities as described in section 2.2.2.

LT-Method: The LT Method was developed by the Martin Centre for Architectural and Urban Studies, Cambridge and is available from the Royal Institute of British Architects, RIBA. The method uses pre-computed data from an integrated energy model to predict the energy consumption for heating, cooling and lighting. The LT-Method is available both as a manual method and a computer-based tool. Much emphasis of the LT Method is on the optimisation of the window area of a building to obtain a balance between thermal and daylight performance.

Energy 10: Energy 10 was developed by the Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory and the Berkley Solar Group. The program utilises a thermal and a simplified lighting simulation engine and has the aim of providing guidance for the design of low-energy buildings with a size of 1000 m^2 or less in order to assist architects, engineers, consultants, student and energy specialists.

Building Design Advisor (BDA): BDA has been developed by the Lawrence Berkeley National Laboratory in the United States with the objective of creating a software structure that supports the integrated use of multiple analysis and visualisation tools. While BDA is still under development, so far two simulation tools have been integrated into the software: an energy estimation tool and a daylighting tool. The aim is to include additional features such as air flow modelling and cost analysis, and to replace the current integrated simulation tools with more advanced simulation engines.

2.4.2 Evaluation of different simulation programs

In this section the four selected simulation programs are evaluated. Assessments of simulation programs have already been carried out in the past [Wiltshire and Wright 1987, Wiltshire and Wright 1989, THERMIE 1994, Robinson 1996, Donn 1997, de Groot 1999, Hien et al 2000, Hong et al 2000], some of which evaluated specific simulation programs, others evaluated in general the capabilities and functionality simulation programs currently provide[1].

The aspects that are addressed here were identified in the initial stages of the research as important for the integration of simulation into the building design process. A number of them had already been addressed in the previous research works and their findings included in the following discussion (they are then referenced at the appropriate location). The ratings that are defined are the opinion of the author taking into account the evaluation outcomes of the assessments referred to above.

[1] Some of the references included date back several years. This is due to the fact that the author found that research in this field is not carried out as often as one might expect (This was also confirmed by [Crawley 2002]).

Table 2.2 lists the different aspects that have been addressed in the evaluation. For model use issues, five rating levels were specified (++, +, 0, -, --), with ++ being a very positive rating, 0 neutral and - - pointing out significant limitations. For the second part of the table, the evaluation of the simulation result types provided, the rating only distinguishes between results provided by the tool (+) or not included (-) (bottom five lines of table).

	BDA	Energy 10	LT-Method	ESP-r
Ease of use	-	-	+	--
Detail in model definition	+	-	--	++
Time required to create a model	-	+	+	--
Data exchange between different users	+	-	-	+
Annual energy consumption	+	+	+	+
Monthly energy consumption	+	+	-	+
Hourly energy consumption	-	-	-	+
Comfort studies	-	+	-/+[1]	+
Energy breakdowns	-	+	-	+

Table 2.2: Rating of different simulation program functions

Ease of use

Ease of use (or 'user friendliness') is a universally applied term in the software world. However, different user groups will respond differently to this issue. A frequent user of an advanced simulation program will have no problem operating its complex interface, but this is not the case for the occasional user of the same software. It is interesting that the threshold under which users refuse to use a program varies significantly with the cultural background of the user. Asian users for example are prepared to spend considerably longer to accomplish certain tasks using a software tool [Woodward 2001]. However, under a time constrained design situation a program that is not user friendly can be inapplicable because the model creation process is too time consuming. The issue of ease of use has hence been generally acknowledged as important for the integration of simulation into the design process and has been addressed in some way in many of the above listed research publications [THERMIE 1994, Robinson 1996, Donn 1997, de Groot 1999].

Of the above listed simulation programs only the LT-Method is reasonably easy to operate for a non-frequent user [THERMIE 1994, Robinson 1996, SESG 2000]. Both the manual method and the computer-based tool are fairly easy to operate and repeating a simulation exercise after not using the program for a long time is not too difficult.

[1] Only some release versions of the LT-Method allow the user to carry out a comfort assessment.

BDA and Energy 10 are more difficult in their operation. De Groot [1999] indicates that it is currently complicated to specify a model geometry with the BDA CAD tool and that input data also has to be specified in American units. It was found during the testing of the program as part of this research that the software is not intuitive. For the Energy 10 tool de Groot [1999] suggests that the program was designed for engineers and thus may not appeal to architects.

The most complex program of those evaluated is the ESP-r system. To use ESP-r, the user needs to have a detailed understanding of what tasks to accomplish in order to create a simulation model, and once this is established, only routine use of the program ensures that the user will accomplish these tasks efficiently. In addition, ESP-r is the only program evaluated that does not automatically default input data (e.g. internal heat gains, ventilation rates or constructions). Consequently, the user of the program will need to have fairly detailed knowledge of the building services aspects of the building in order to ensure accurate data specifications in the model.

Detail in model definition

Depending on the program, simulation models can be defined at different levels of detail. Window properties, for example, can be specified as a percentage of the façade area or by specifying the dimensions of the window and its location within the external wall. Construction specifications can vary from the simple definition of the construction type (e.g. cavity wall) to a detailed material and thickness specification for the different layers.

It is generally not necessary to define a simulation model to the most accurate level available; sometimes a simpler data definition will provide sufficiently accurate results [CIBSE 1998]. For certain thermal simulations it is adequate to express window area as the percentage of the façade (e.g. when determining the heating energy consumption required in a space). However, when determining daylight factors in a room more detailed window data definition is important. The possible detail in model description is an important consideration when using simulation and has consequently been addressed in past simulation tool appraisals [Wiltshire and Wright 1987, Wiltshire and Wright 1989, Robinson 1996, Hien et al 2000].

Of the programs tested, ESP-r allowed the user by far the most detailed model definition. The BDA standard model definition is as in depth as for the ESP-r system, but the program is limited when it comes to the specification of advanced design representations in a simulation model. ESP-r allows, for example, the specification of complex heating and cooling control strategies, blind control and local specification of convective heat transfer coefficients. This is not possible with BDA. Energy 10 approaches model data definition in a more simplified way than ESP-r or BDA. In this case, the model comprises only two zones, resulting in a fairly crude representation of the building design. All other data (e.g. air leakage, insulation, thermal mass) are initially specified on the basis of yes/no-values, and although the user can alter these values later, the two-zone approach still produces the risk of considerable discrepancies between the actual building and its simulation model. The LT method allows a fairly complex zoning of the building, differentiating different locations in the building (core or perimeter zones) as well as different orientations. However, the specification of input data such as internal heat gains, massing of the building or the insulation level of the envelope is restricted to a limited number of possible standard selections. Other model data such as heating and cooling setpoints cannot be specified at all.

Time requirements to create a model

The time required to create a simulation model varies significantly for the tools evaluated. The LT-method has the least time requirements for model creation. After measuring or calculating the zone areas the user can within minutes determine the energy requirements of the building. The AutoBuild function of Energy 10 also allows the specification of a simulation model in a few steps and only requires the specification of five input parameters: building location, use category, size, HVAC system and utility rate. The model definition with the BDA takes longer because of the complex and time consuming process of specifying model geometry. However, for the different zones and surfaces attributions such as internal heat gains, heating and cooling control, ventilation rates and construction, defaults are used to speed up the model creation process. The ESP-r system has the most time-consuming model creation process: every zone and surface entity needs to be specified manually. Some support can be obtained from predefined operational profiles (internal heat gains, scheduled ventilation rates) but users of the program rarely apply this function.

Data exchange between different users of a tool

Rapid developments in the IT sector already start to affect the building design process. Data and information exchange (including drawings) take place more and more frequently in electronic format, and this trend will increase in the future. This has significant consequences on the way building designers work: it is possible for designers located at different locations to work together almost as if they were located at the same place [McGaffin and Hyett 1998, Mahdavi et al 1999]. Simulation programs will therefore have to be developed in a way that fits into this emerging design environments.

Both ESP-r and BDA allow the export of a simulation model to another user. For this purpose both programs have facilities that allow the automatic creation of an "export file" of a model. With both the LT-Method and Energy 10 a model transfer between different users is not possible. This has been stated as a limitation in a recent LT-Method workshop [SESG 2000].

Results output provided

The result outputs produced by the different simulation tools vary significantly. Some programs provide only data about the heating and cooling energy consumption; others include results related to the comfort conditions in the building (e.g. resultant temperature in a space). Some programs also give information about the energy flows within the building and specify data such as solar gains or heat flows within constructions, storage effect, etc. For each results output the level of detail included can again vary. Heating or cooling energy consumption can be defined by an annual figure, but also with detailed hourly profiles. The latter allows a more detailed investigation of the building behaviour. Another issue is to what extent a program produces information about energy flows in the building. Again, these issues have been addressed in past research [Wiltshire and Wright 1987, Wiltshire and Wright 1989, THERMIE 1994].

The LT method specifies the energy consumption of the building only as an annual figure, whereas BDA, Energy 10 and ESP-r also provide monthly figures. In addition, ESP-r produces hourly energy consumption predictions. ESP-r and Energy 10 show temperature profiles in the building, the LT method and BDA do not (although some versions of the LT-method predict annual overheating hours for the case when the building is not air conditioned). With the LT-Method and the BDA it is not possible to examine the energy flows in a building by looking at the energy breakdowns. It is also not possible to check temperature profiles over a day. ESP-r and Energy 10 do provide these facilities.

The LT-Method and Energy 10 also explicitly state that the tools have been developed for design comparison purposes rather than to predict absolute figures. As previously mentioned, simulation tools such as the ESP-r system have been developed with the aim of producing performance predictions that are as close as possible to the real performance of the building.

2.4.3 Comparative discussion

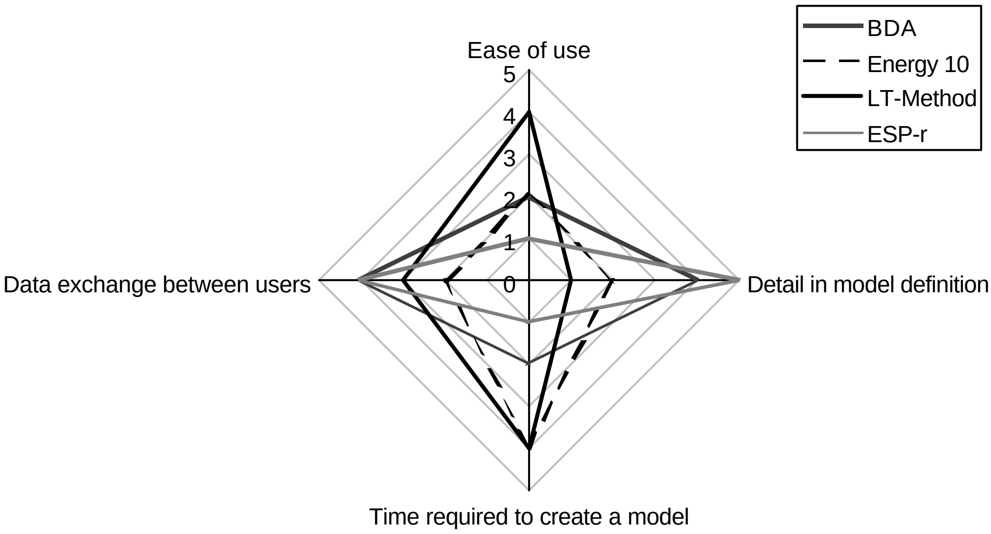


Figure 2.10: Radar graph of the ratings of the different simulation programs (In the graph a high rating of ++ is equivalent to 5, a poor rating of -- equates to 1)

Figure 2.10 shows a radar graph that illustrates the ranking of the various programs with respect to their user functions based on table 2.2. Several observations can be made:

- There are significant differences in the time requirements for the creation of and the detail in model definition.
- There are significant differences in the ease of use of simulation programs. Apart from the LT-Method, most programs were rated low with respect to their ease of use. The worst rating was given to the ESP-r system.
- Interfaces of most simulation programs have not yet been developed to a degree where a simulation model can be created effortlessly.
- Programs that allow a quick model definition have restrictions in the modelling detail the user can specify.
- Figure 2.10 also illustrates a strong correlation between the time spent to create a simulation model and the detail in the possible model definition. It can be seen that with both ESP-r and BDA considerable time is required to produce a simulation model, but the models have the greater detail in comparison to the LT-Method and Energy 10. This fact is supported by findings described earlier in section 2.4.2.

Table 2.3 displays from Table 2.2 the rating of the performance predictions that the different simulation programs provide. The main observations are again also based on research mentioned earlier in section 2.4.2:

- The LT-Method, with the best rating for ease of use, provides the least information on buildings performance.
- Despite the fact that the BDA allows a detailed model definition (what also results in a more time consuming definition process) the program only provides limited performance information.
- The only program that deals with all result outputs was the ESP-r system.

	BDA	Energy 10	LT-Method	ESP-r
Annual energy consumptions	+	+	+	+
Monthly energy consumptions	+	+	-	+
Hourly energy consumptions	-	-	-	+
Comfort studies	-	+	-/+	+
Energy breakdowns	-	+	-	+

Table 2.3: Performance predictions provided by the different simulation programs

2.5 Barriers for the application of advanced simulation programs like ESP-r

The previous sections indicated advantages that the contemporary building design process could gain from the application of advanced building simulation programs. However, it was also concluded in section 1.6 that simulation only finds limited application in the contemporary building design process. This raises the question of reasons behind the restricted use of simulation within the building design process. This section discusses barriers that have been identified during the research as to why the tools have not yet found wider application among design practitioners.

2.5.1 Relative unimportance of energy efficiency

It was indicated in section 1.5 that energy efficiency is often subordinated and more priority is given to other design considerations. Despite the fact that it is not unusual for a client to ask for a ‘green’ building design, it is often other considerations (like the cost of a building project) that form the basis for the ultimate decision making in the design process (Badger [2002], a senior project manager on large PFI projects within the architectural design company where a considerable part of the research described in this thesis was carried out quoted this as an observation he has made frequently).

This is a barrier that cannot be addressed as part of this research on how to advance simulation tools so that they are of use for practitioners and was hence not addressed in this work. The unimportance of energy efficiency can however be seen as a cause for the limited application of building simulation. During the creation of a building design designers can therefore pay limited attention to energy and environmental performance issues and still satisfy the expectations of the client. Alternatively, if the designer decides to still ensure that the building design has a good energy and environmental performance the issue of resources arises. It will either be necessary to convince the client that it is worth to pay for the additional cost of the analysis or the cost has to be covered by the overall budget of the project. It may be concluded that in such situations the designer will only make these efforts if he/she takes a personal interest in energy and environmental design issues.

Nevertheless, the discussion in section 1.2 regarding changes in the UK Building Regulations had concluded that in future it may be necessary to consider the energy and environmental performance of a building when trying to obtain approval for innovative design concepts (e.g. a building design with a fully glazed façade) – and innovation is a field that many clients find of interest. Such developments may therefore generally support an increased attention to energy and environmental design consideration and also support the application of simulation within the building design process.

2.5.2 No structure for inclusion of simulation in the design process

Section 2.2 showed how simulation capabilities have advanced over time. This has resulted in a situation where advanced simulation programs allow the evaluation of the same design aspect (e.g. ventilation) with different types of simulation models (e.g. scheduled air flow rates, air flow networks)[1]. Different approaches normally result in differences in the performance predictions, but also in the time requirements in creating the model as well as in the knowledge required by the user to create the model.

Experts in the use of simulation are generally capable of deciding which type of simulation study is appropriate to support design decision making at a certain design stage (taking into account issues such as time requirements, data availability, results reliability, etc.). The situation becomes different when decisions have to be made by a user with only a limited background in energy and environmental performance issues. For such a user it is difficult to decide which simulation study is feasible at a particular design stage. In order to integrate simulation into the overall design process, it is therefore necessary to develop procedures that allow designers to utilise building simulation at different building design stages [Mahdavi et al 1993].

[1] Hensen at al [1996] illustrate this with an example of different possibilities to evaluate the ventilation scheme of a single room.

It is therefore not sufficient to focus research efforts only on the development of new simulation functionalities and capabilities but it is also important to investigate how they can be utilised within the building design process. As long as this is unclear to building designers it will be very difficult to make them use this design support tool. This observation is also supported by De Wilde et al [1998] who state that: *[the] future class of simulation tools [should] adapt to the design process, and not vice versa*. This is an issue that has not really found consideration in the development of contemporary advanced simulation tools.

2.5.3 Complex user functionality

Frequent users of building simulation programs are generally confident in the application of the software. They are familiar with the tasks involved in the creation of a simulation model and know how to navigate through the program in order to carry them out. However, the creation of a building simulation model with an advanced simulation program is not a trivial task. The daily application of the tool is required in order to stay familiar with its operation [Andre and Nicolas 1994]. It will be shown later (section 3.3) that this cannot be assumed for users who will typically use the tool at different building design stages. Keil et al [1995] state that, especially for non-frequent users of a design support tool, usefulness will not compensate for a lack of ease of use and will result in rejection of the tool. It will be shown later in this thesis that this is an issue also of relevance for the application of dynamic building simulation in the building design process (section 3.3). If it is intended to enable non-frequent users to operate building simulation programs it is important to develop a software tool that gives a maximum amount of guidance and which is as intuitive as possible, both for the model creation process and the results analysis[1].

Robinson [1994] distinguishes between the different philosophies in interface developments with the term simulation language and simulator, where the former relates to an advanced simulation tool that offers full flexibility in the model creation, whereas the latter stands for purpose-designed software that simulates a specific range of parameters. Simulators are generally menu driven, construction of models is faster, but they are less flexible than the simulation languages. Figure 2.11 summarises their main characteristics. Clarke and Mac Randal [1993] aimed to address the issue of different user groups by developing a simulation tool that had different user functions depending on the background

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[1] The development of tools that respond to the background of the user and have functions that allow the quick and easy performance of an assessment is an issue that does not only relate to building simulation but is a general consideration when developing Design Decision Support Systems (Do 1996).

of the user. However, the concept was never implemented in a software tool which is currently available for designers.

Feature	Simulator	Simulation Language
Modelling flexibility	→	→
Duration of model build	→	→
Ease of use	←	←
Time to obtain modelling skills	→	→

Figure 2.11: Comparison between simulators and simulation languages (after Robinson [1994])
(Lower → Higher)

2.5.4 Limited performance prediction analysis

The efficient analysis of performance predictions obtained from a simulation exercise is as important as a quick and reliable model definition process. The time required to carry out such an analysis with the tools currently available can be considerable, depending on the type of investigation carried out. Consequently, the users of the programs often draw conclusions from a simulation exercise by having a look at high level performance criteria (e.g. overheating hours or energy consumptions) without interrogating reasons behind this performance [Ho 1999].

In addition, the advanced simulation programs currently available often do not give sufficient support to the user in carrying such an investigation [Soebarto and Williamson 1999]. However, when using building simulation throughout the design process the situation becomes even more complex. At the different design stages, designers will require varying types of information and it will be users with different backgrounds (architects or engineers) to whom this information is going to be presented.

2.5.5 Uncertainty

Uncertainty of input data is an important aspect of building performance predictions [De Wit 2001, Macdonald et al 1999]. Especially at the early design stage, designers are often not in a position to specify certain data types (e.g. internal heat gains in an office space). On the contrary, they might actually prefer to specify a potential data range and hence obtain a better understanding of how the building is likely to perform under different conditions. Uncertainty can occur in numerous model entities, including climatic data, form and fabric, ventilation, occupancy behaviour and systems control. The routine consideration of uncertainty by simulation programs would allow the analysis of a building in a more holistic way.

2.5.6 Validation

Validation has been an issue since the introduction of the first simulation programs (see as an example [Strachan 2000] which lists numerous validation exercises carried out for the ESP-r system). Clarke [2001] points out that ultimately a program's predictive accuracy can only be assessed by comparing its outputs with buildings in use. Such a validation exercise would be complex technically and expensive, and can only be pursued in well-resourced projects. With respect to the ESP-r system Clarke states that while the program performed well in one project it sometimes failed when a similar test was repeated in another project. The complex issue of validation has resulted in the development of diagnostic test such as BESTEST [Judkoff and Neymark 1995] for the evaluation of new simulation programs.

Nevertheless, the barrier of distrust by some designers in performance predictions does remain. In this context it should be emphasised that inaccurate performance predictions can also be caused by incorrect model specifications by program users.

2.6 Initiatives to advance the use of simulation in the building design process

2.6.1 Scottish Energy Systems Group (SESG)

The SESG [McElroy and Clarke 1999, SESG 2003] is a joint Scottish Office, Industry and Scottish Enterprise venture which aims to transfer simulation to energy sector companies and to support this transfer in the context of day-to-day work practices. The group is a successor of the Energy Design Advice Scheme (EDAS), another UK Government initiative that delivered external design advice supported by simulation exercises. The intention is to demonstrate that simulation-based design can yield useful results, quicker, cheaper and better than conventional methods.

Although the SESG's main focus is on the built environment, the group supports in principle every company or organisation that works in the energy or environmental sector that can utilise the benefit of simulation. Members of SESG are 30 design engineering companies, 10 architectural practices, 1 multidisciplinary design practice, 3 local authorities, 2 manufacturers and 2 University departments. Based on a survey the SESG estimates that efforts made by the organisation resulted so far in energy savings of around 66.5 million kWh.

The SESG conducts technology transfer in two main ways: Supported Technology Deployments (STDs) and through Advocacy Groups.

STDs [McElroy and Clarke 1999] are the mechanism by which SESG members are able to obtain in-house support from modelling specialists seconded to the design team. The aim is to allow practitioners to gain risk-free access to simulation in the context of live projects and otherwise normal work practices. This scheme can be supported by a loan pool of computers with already installed simulation software – the companies also have the option to purchase the computer at the end of the STD. So far the SESG has carried out over 50 STDs, with 24 companies also benefiting from the loan pool program and several also purchasing a computer..

Advocacy Groups are formed with members of different design teams. This allows the group to explore issues together and thereby to identify opportunities for, and barriers to, the effective application of simulation in their area. Their views are disseminated through SESG newsletters and workshops.

In addition to STDs and Advocacy Groups the SESG also organises information days, seminars, training days and workshops.

2.6.2 Solaroptimierte Gebäude mit minimialem Energiebedarf

"Solaroptimierte Gebäude mit minimialem Energiebedarf" (Solar optimised buildings with minimum energy consumption) is an initiative by the German government with the aim of enhancing the use of simulation in the building design process. The program is new for Germany because it is an alteration from the usual research funding scheme which had until then focused on building components (e.g. transparent insulation, photovoltaic systems or energy efficient heating systems).

Funded projects are non-residential buildings with public access. The overall building energy consumption has to be below 70 kWh/m^2a and the heating energy consumption must not exceed 40 kWh/m^2a. The buildings are also monitored during occupation to find out whether the predictions during the building design were correct. Building design and monitoring is carried out in close collaboration with Universities to ensure that education benefits from knowledge and experience gained.

2.6.3 Discussion

Although the German initiative promotes simulation within building design it also relates specifically to highly energy efficient building design and not to routine building design. Another observation is that many architects involved in the project have past experience in the design of energy efficient buildings – some have played a key role in their promotion.

It seems likely that the approach of the SESG will (at least in the short term) have a greater impact on the wider use of simulation among general practitioners because it presents simulation as a tool that can make contributions to any type of design project. The group also tries to utilise experience gained from the work with general practitioners for the enhancement of simulation tools. This is reflected in the fact that the SESG also endeavours to feed information back to developers and vendors of commercial software packages.

2.7 Closing remarks

This chapter provides an overview of available building simulation software programs. It described the evolution of dynamic building simulation programs to software tools that allow detailed analysis of a building design proposal and pointed explained simulation can be applied as a tool de-coupled from the design process or as an integrated application. It was emphasised that efforts to increase the application of simulation in the building design process should also encourage the integrated application of tools.

A comparative analysis of different simulation tools which was based on past research and analysis by the author concluded that most of the simulation tools are still not easy to operate and that tools that allow a quick model definition do not allow a detailed model specification.

The chapter also introduced two initiatives that have been established to advance the application of simulation in the building design process. It was stated that the German initiative ("Solaroptimierte Gebäude mit minimialem Energiebedarf") relates simulation mostly to very energy efficient building design whereas the Scottish Energy Systems Group emphasises the fact that simulation can be applied in any design project. In this context a general observation by the author is the fact that despite an extensive literature search no references were found for similar initiatives in other countries.

On a general level the conclusion can be drawn that simulation programs do not fully address the needs of building designers. This is a consequence of the fact that simulation programs still have not been developed to a degree that they could be classified as 4th generation tools as outlined in section 2.2.1 of this chapter.

After having obtained from this chapter an understanding of capabilities and potential application of simulation programs, the next chapter discusses how these tools could be better integrated into the building design process.

References

THERMIE, "Tools and Techniques for the Design and Evaluation of Energy Efficient Buildings", THERMIE Action No B184, Produced for the European Commission Directorate-General for Energy, 1994.

Andre P, Nicolas J, "Use of an Integrated Software System for Building Design and System Simulation", Proceedings of the Conference of Systems Simulation in Buildings, Liege, Belgium, 1994.

Badger C, Project Director at HLM Design, Personal Communication, 2002.

Baker N V, Steemers K, "The LT Method, Version 2 – an Energy Support Tool for Non-Domestic Buildings" (The LT Method was Developed by the Martin Centre for Architectural and Urban Studies, Cambridge and is Available from the Royal Institute of British Architects, RIBA).

CIBSE, "Building Energy and Environmental Modelling", CIBSE Application Manual AM 11, CIBSE, 1998.

Clarke J A, "Energy Simulation in Building Design", Butterworth-Heinemann, Oxford, 2001.

Clarke J A, "Environmental Systems Performance", PhD Thesis University of Strathclyde, 1977.

Clarke J A, Hand J W, Janak M, "Integrated Performance Appraisal of Daylight Buildings", Proceedings Daylighting 1998, an International Conference for Daylighting Technologies for Energy Efficiency in Buildings, Ottawa, Ontario, pp 71-78, 1998.

Clarke J A, Mac Randal, "Implementation of Simulation Based Design Tools in Practice", Proceedings Building Simulation 93, Adelaide, pp 423-429, 1993.

Cooper G, Rezqui Y, Jackson M, Lawson B, Peng G, Cerulli C, "A CAD-based Decision Support System for the Design Stage of a Construction Project", Proceedings of the 5th International Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, Eindhoven, pp 91-100, 2000.

Crawley D B, Software Demonstration at Building Simulation 01, Rio de Janeiro, 2001.

Crawley D B, Winkelmann F C, Lawrie L K, Petersen C O, "EnergyPlus: New Capabilities in a Whole-Building Energy Simulation Program", Proceedings Building Simulation 01, Rio de Janeiro, pp 51-58, 2001.

De Groot E, “Integrated Lighting System Assistant”, PhD Thesis, Technische Universiteit Eindhoven, 1999.

De Wilde P, Van der Voorden M, Augenbroe G, “Towards a Strategy for the Use of Simulation Tools as Support Instrument in Building Design”, Proceedings of the Conference of Systems Simulation in Buildings, Liege, Belgium, 1998.

De Wit S, “Uncertainty in Predictions of Thermal Comfort in Buildings”, PhD Thesis, Technische Universiteit Delft, 2001.

Do E Y, “The Right Tool at the Right Time – Drawing as an Interface to Knowledge Based Design Aids”, Proceedings Association for Computer Aided Design in Architecture (ACAIDA ’96), 1996.

DOE (US Department of Energy), “Energy Tools Directory”, www.energytools.gov, 2002;

Donn M R, “A Survey of Users of Thermal Simulation Programs”, pp 65-72, Proceedings Building Simulation 97, Prague, pp 65-72, 1997.

Dorer V, Haas A, Keilholz W, Pelletret R, Weber A, “COMIS V.3.1 Simulation Environment for Multizone Air Flow and Pollutant Transport Modelling”, Proceedings Building Simulation 01, Rio de Janeiro, pp 403-410, 2001.

ESRU, “ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series”, University of Strathclyde, Glasgow, 2002.

Glaser D C, “Downloadable PowerPoint Presentation from June 2002”, http://www.cs.berkeley.edu/~dcg/infovis2001/, 2002.

Glaser D C, Personal Communication, 2001.

Glaser D C, Ubbelohde M S, “Visualisation for Time Dependent Building Simulation”, Proceedings Building Simulation 01, Rio de Janeiro, pp 423-429, 2001.

Gonzalo R, “Energiebewusst Bauen”, Edition Erasmus, 1994.

Hand J W, “How to Train Users of Simulation Based Thermal Performance Analysis Tools”, Proceedings Building Simulation 93, Adelaide, pp 93-102, 1995.

Hand J W, “Removing Barriers to the Use of Simulation in the Building Design Professions”, PhD Thesis University of Strathclyde, 1998.

Hand J W, Hensen J L M, “Recent Experiences and Developments in the Training of Simulationists”, Proceedings Building Simulation 95, Madison, Wisconsin, pp 346-353, 1995.

Hand J W, Personal Communication, 2000.

Hensen J L M, “On the Thermal Interactions of Building Structure and Heating and Ventilation Systems”, PhD Thesis, Technische Universiteit Eindhoven, 1991.

Hensen J L M, Hamelinck M J H, Loomans M G L C, "Modelling Approaches for Displacement Ventilation in Offices", Proceedings of the 5th International Conference on Air Distribution in Rooms (ROOMVENT 96), Yokohama, 1996.

Hien, W N, Poh L K, Feriadi H, "The Use of Performance-based Simulation Tools for Building Design and Evaluation – a Singapore Perspective", Building and Environment, Volume 35, pp 709-736, 2000.

Ho C, Personal Communication, 1999 .

Hong, T, Chou S K, Bong T Y, "Building Simulation: an Overview of Developments and Information Sources", Building and Environment, Vol. 35, pp 347-361, 2000.

Janak M, "The Run Time Coupling of Global Illumination and Building Energy Simulation", Proceedings Daylight, An International Conference on Daylight Technologies for Energy Efficiency in Buildings, Ottawa, pp 113-120, 1998.

Jones P, "Energy in Buildings", Workshop Organised by the Chartered Institution of Building Services Engineers (CIBSE), Manchester, 2001.

Judkoff R, Neymark J, "International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method", Report TP-472-6231, Goldelv CO, National Renewable Energy Laboratory, 1995.

Keil M, Beranek P M, Konsynski B R, " Usefulness and Ease of Use: Field Study Evidence regarding Task Considerations", Decision Support Systems, Volume 13, pp 75-91, 1995.

Kelly, N J, "Towards a Design Environment for Building Integrated Energy Systems – The Integration of Electrical Power Flow Modelling within Building Simulation", PhD Thesis University of Strathclyde, 1998.

Kühner S, "Visualisierung von Ergebnissen numerischer Simulationen von Luftströmungen in und um Bauwerke in einer Virtual Reality Umgebung" (Visualization of Results from Numerical Simulations of Indoor and Outdoor Flow in a Virtual Reality Environment), Diploma Thesis, Lehrstuhl für Bauinformatik, TU München, September 1999.

LBNL (Lawrence Berkeley National Laboratory), "Building Design Advisor Homepage", http://kmp.lbl.gov/BDA, 2002.

Lechner N, "Heating, Cooling, Lighting – Design Methods for Architects", John Wiley and Sons, 2001.

LESO-PB, EPFL, Glazing Systems Design Tool, EPFL, Lausanne, Switzerland, 1998.

Macdonald I A, Clarke J A Strachan P A, “Assessing Uncertainty in Building Simulation”, Proceedings Building Simulation 99, Kyoto, pp 683-690, 1999.

Mahdavi A, Hartkopf V, Loftness V, Lam K P, “Simulation-based Performance Evaluation as a Design Decision Support Strategy: Experiences with the Intelligent Workplace”, Proceedings Building Simulation 93, pp 185-191, 1993.

Mahdavi A, Ilal M E, Mathew P, Ries R, Suter G, “Aspects of S2”, Proceedings of the 8th International Conference of Computer Aided Architectural Design Futures (CAAD FUTURES), Atlanta, USA, pp 185-196, 1999.

McElroy L B, Clarke J A, “Embedding Simulation Within Energy Sector Businesses”, Proceedings Building Simulation 99, Kyoto, pp 263-268, 1999.

McGaffin K, Hyett P, “Internet for Beginners”, The Architects’ Journal, Vol. 207, No 15, pp 46-47, 1998.

Negrao, C O R, “Conflation of Computational Fluid Dynamics and Building Thermal Simulation”, PhD Thesis University of Strathclyde, 1995.

NREL (National Renewable Energy Laboratory), ”Energy 10 Homepage”, http://www.nrel.gov/buildings/energy10, 2002.

Robinson D, “Energy Model Usage in Building Design: a Qualitative Assessment”, Building Services Engineering Research and Technology, Vol. 17, No. 2, CIBSE, pp 89-95, 1996.

Robinson S, “Successful Simulation – a Practical Approach to Simulation Projects”, McGraw-Hill Book Company, 1994.

Schneider A, “Solararchitektur für Europa”, Birkhäuser Verlag, 1996.

SESG (Scottish Energy Systems Group), “Report on the Deployment of LT and LTr into design practice”, HOTNEWS (Newsletter of the SESG Energy Systems Group), 2000.

SESG (Scottish Energy Systems Group), “SESG relaunched”, HOTNEWS (Newsletter of the SESG Energy Systems Group), 2003.

Soebarto V I, Williamson T J, “Designer Orientated Performance Evaluation of Buildings”, Proceedings Building Simulation 99, Kyoto, pp 225-232, 1999.

Strachan P A, “ESP-r: Summary of Validation Studies Technical Report”, Glasgow, University of Strathclyde, Energy Systems Research Unit (ESRU), 2000.

Tufte E R, “The Visual Display of Quantitative Information”, Graphics Press, Cheshire, Connecticut, 1983.

Van Leeuwen J P, Assistant Professor at the Technische Universiteit Eindhoven and involved in Design System Group, which also deals with Virtual Reality Systems, Personal Communication, 2001.

Wiltshire J, Wright A, "The Documentation and Evaluation of Building Simulation Models", Building Environmental Performance Analysis Club, 1989.

Wiltshire J, Wright A, "The Evaluation of Simulation Models ESP, HTB2 and SERI-RES for the UK Passive Solar Programme", Report Prepared for the Energy Technology Support Unit of the Department of Energy, 1987.

Woodward B, Technical Director Informatix Software Systems, Personal Communication, 2001.

CHAPTER 3

THE SIMULATION SUPPORTED DESIGN PROCESS (SSDP)

3.1 Introduction

Dynamic building simulation was presented in the previous chapter as a DDSS that enables the designer to assess the energy consumption and comfort conditions that can be expected from a building. This chapter describes research carried out to enable the efficient utilisation of simulation in the building design process: the development of a concept for a simulation supported design process (SSDP). The first section of this chapter contains an overview of the different phases of the building design process, followed by a discussion of how simulation can be used to carry out energy and environmental analysis at the different design stages. This is followed by a specification for a SSDP and a description of the implementation platform chosen for this research. Following this, the chapter deals with the selection and definition of design parameters to be evaluated with the SSDP at the various stages of the building design process, followed by the definition of the focus for its implementation.

3.2 The RIBA Design Stages

The structure of the SSDP was based on the RIBA Design Plan of Work [RIBA 1995], which divides the design process into different stages. The plan of work is widely recognised in the UK construction industry and associated professions as a model set of procedures for building project administration. Using the RIBA plan had two benefits: (1) it is based on a structure the designers are already familiar with, thus making it easier for them to accommodate the idea of using simulation within a recognised design process; (2) it is likely that architects (at least in the UK) will follow, to a certain degree, the design process described in the document.

The RIBA plan groups the building design process into twelve different work stages, ranging from an Inception Stage where the first contact with the client is made to a Feedback Stage at the end of the project. The stages are described briefly in Table 3.1. Three design stages were identified where simulation can make a contribution to an improved building design (see also Figure 3.1):

- Outline Design Stage
- Scheme Design Stage
- Detailed Design Stage

Reasons for the selection of these 3 stages is discussed in the following. The choice was made based on findings from discussions between the author and architects of the company where research into the SSDP was carried out.

Work Stage	Description
A: Inception	Discuss the client's requirements including timescale and financial limits; assess these and give general advice on how to proceed.
B: Feasibility	Carry out a study to determine the feasibility of the client's requirements.
C: Outline	Analyse the client's requirements; prepare outline proposal and an approximation of the construction cost.
D: Scheme	Develop a scheme design sufficiently accurate to illustrate special arrangements, materials and appearance.
E: Detail	Detailed definition of design.
F and G: Production and Bills	Prepare production information (drawings, materials, workmanship); prepare bills of quantities.
H: Tender	Invite tenders.
J: Project Planning	Appointment of contractor.
K: Operation on site	Administer construction operations on site.
L: Completion	Guidance to maintenance, provide drawings to client, including service installations.
M: Feedback	Occupiers evaluate building.

Table 3.1: The RIBA design stages (summarised after [RIBA 1995])

Pre-Design	A ? B
Design	? ? C ? D ? E
Prepare To Build	? ? F ? G ? H
Construction	? ? J ? K ? L
Post-Construction	? ? M

Figure 3.1: RIBA design stages split into phases (after [Kagioglou et al 1998])

Outline Design Stage: During the Outline Design Stage the designers produce a range of design options, which will in the first instance be an intuitive response to factors such as site conditions, size, orientation and views. These options are then analysed and presented in the form of a feasibility study, which shows the design analysis, and options considered. The study will be sufficiently detailed to establish the outline proposal preferred. The analysis also includes a cost appraisal.

Scheme Design Stage: The Outline Design Stage proposal, approved by the client, is taken to a more detailed planning level in the Scheme Design Stage. The designer will have to ensure that all the clients' needs and requests are integrated into the design proposal.

Detailed Design Stage: In the Detailed Design Stage the approved Scheme Design solution is worked through in detail. Detailed design drawings are produced for co-ordinating structure, services and specialist installations. Internal spaces may also be detailed to include fittings, equipment and finishes.

During the Inception and Feasibility Stage the designer does not design the building, but determines objectives and constraints that will then influence design decisions. This will normally include planning permission issues, health and safety, a site visit, financial considerations and any other aspect that is relevant for the particular project.

Despite the fact that simulation cannot be applied at these design stages it is still possible to address energy and environmental aspects (see Figure 1.7 in chapter 1), e.g. by pointing out to the client the benefits of investing in environmental design studies or ensuring that the cost for later simulation exercises is considered when the budget for the building is determined and established.

Similarly, after the Detailed Design Stage building simulation can still be used. However, it will then not serve as a Design Decision Support System, but as support for the control and operation of the building services systems [Clarke et al 2001].

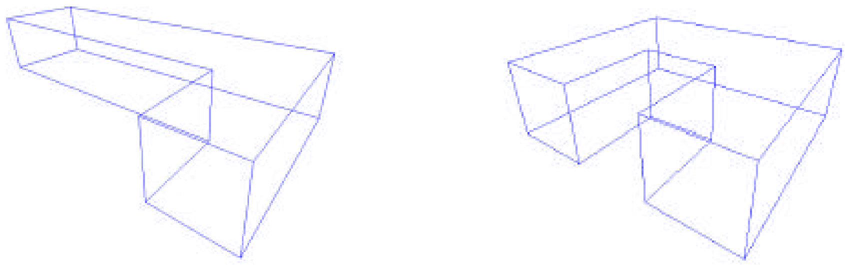
3.3 The potential role of simulation during the design process

So far this chapter has given a description of the various building design stages. This section discusses how simulation can support the design decision making at the Outline, Scheme and Detailed Design Stage.

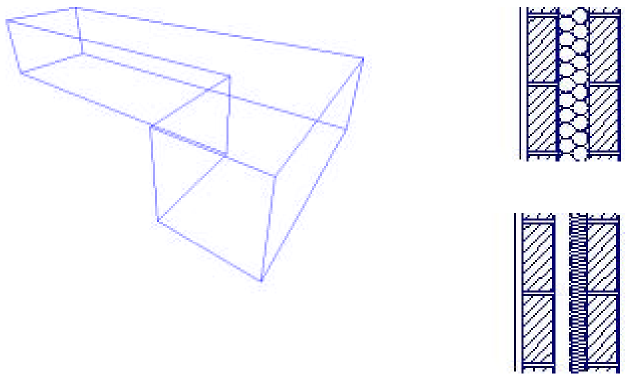
3.3.1 Outline Design Stage

At the Outline Design Stage simulation will be used to understand how design decisions made in this design phase might affect the performance of the building. Since these decisions are likely to fundamentally affect the performance of the finalised building design (e.g. does the building need air conditioning or does natural ventilation provide adequate summer comfort conditions) the application of simulation at this design stage is particularly desirable to ensure that the designer does not give preference to a design concept without realising energy and environmental implications.

The designer should therefore be provided with an indication of the expected building energy consumption and in many cases also the comfort conditions in the building. An analysis should also identify any parameters that may cause problem(s) and the scale and extent of the problem. Simulation can be used to compare the performance that can be expected from different design geometries and/or to evaluate the performance of different designs that are based on one particular geometry (see Figure 3.2).



(a)



(b)

Figure 3.2: Different analyses at the Outline Design Stage: (a) assessment of different geometries (b) analysis of the same geometry by changing the façade construction

The Outline Design Stage is also the design stage with the shortest time available to the designer in terms of decision making: this time pressure needs to be addressed when developing a simulation tool suitable for use at this design stage. If it is too time consuming to create a model the designer will reject the tool – quick turnover times in simulation model creation and performance prediction analysis are vital.

With respect to the typical user of the simulation software at this stage, it is likely that it will be architect who will undertake the simulation exercises. This is due to two main reasons:

- At this stage an architectural company has normally not won the contract for a project, but is competing with other design teams. There will be a limited budget or no fees paid for the simulation work and hence there is no budget to commission a sub-contractor to undertake a simulation exercise. The architects will therefore want to undertake any simulation in-house in a quick (and cheap) manner.

- The design at the Outline Design Stage is undergoing constant and rapid changes. From experience, the designer will be able to assess changes in terms of functionality and aesthetics, but ideally should also be able to undertake a more or less immediate evaluation of the energy and environmental assessment of a design proposal. This is only possible if the simulation is carried out in-house[1].

3.3.2 Scheme Design Stage

In the Scheme Design Stage the designer will want to investigate problem areas that have been identified or to obtain information on how to improve the energy and environmental performance of the building. Most of the simulation exercises at this stage will be carried out for typical sections of the building or in areas where problems have been identified.

Simulation exercises carried out at the Scheme Design Stage are more advanced than the ones described above for the Outline Design Stage and currently they are usually carried out by a simulation specialist. In order to enable architects to undertake these studies routinely, significant changes would be required to current building simulation tools. However, for a number of reasons this would also be a desirable development:

- Design decisions at the Scheme Design Stage can significantly affect the aesthetics of the building, an import design aspect for architects. If it is possible for architects to undertake simulations themselves they will thus be less detached from the technical aspect of these design decisions than is currently the case.
- Commissioning somebody else with the assessment of a building design might not allow the architect to further investigate issues that may become obvious after

[1] Other research (de Wilde et al 2001) points out that in low energy building design significant decisions about the application of advanced energy efficiency design features are made without the backup or support from simulation (e.g. the use of solar hot water systems, PV panels). De Wilde (2001) also states that these simulations cannot be carried out by architects but by simulation experts, requiring more time for the Outline Design Stage. From the research undertaken as part of this project it seems likely that such decisions are indeed made at early design stages. It is also true that such simulation exercises would have to be carried out by simulation experts. However, although it might be that a client interested in a low energy building design will also be prepared to allow additional time to undertake simulation exercises it is questionable whether this longer duration of the design process will be acceptable in a general design situation.

viewing performance predictions obtained from a simulation exercise, hence the tool is not used to its full potential.

3.3.3 Detailed Design Stage

During the Detailed Design Stage, the building design is progressed in detail. By finalising a large number of design parameters, the designer will have removed significant uncertainty that was contained in simulation models of earlier building design stages. This data accuracy is a necessity for the advanced simulation exercises that will be carried out at the Detailed Design Stage, e.g. the design of an air conditioning or natural ventilation system. In contrast to the Scheme Design Stage where simulation was employed to give a general indication of the performance that could be anticipated from a design, the design of such building services system requires reliable input data.

Checking the robustness of a building design is another area where building simulation is applied to address issues such as the summer comfort conditions of a building and the performance of a heating plant during extreme winter conditions. Currently these design checks are often the only way in which simulation is applied in the design process [Hien et al 2000, Clarke 2000]. At the Detailed Design Stage simulation also finds the widest application in the building design process.

In this context it should also be emphasised that currently for some building projects such a performance prediction analysis is not only carried out during the detailed design stage but even during the construction phase. This illustrates the ineffective manner in which simulation is currently applied within the built environment. With the routine application of the SSDP this approach should not be taken any more.

3.4 Design specification for the SSDP

After having described how simulation can contribute towards an improved performance and quality of the building design, this section provides design specifications for the SSDP, covering the following issues:

- Allow evaluation of relevant design parameters;
- include flexibility for future design trends or building technologies;
- produce simulation tools that will be accepted by designers;
- produce maximum results accuracy.

They form the basis of SSDP implementation concept which is displayed in figure 3.3. The specification is the result of research by the author which was carried out by means of observations and discussions with designers but was also influenced by the author's knowledge about state-of-the-art simulation capabilities. The approach will be discussed in section 3.6.1 and justified in section 3.6.2, but benefits of the SSDP will be illustrated throughout the thesis.

3.4.1 Allow evaluation of relevant design parameters

The previous section describes how a design team will use simulation differently at the various building design stages. At the beginning of the design process they will use simulation to determine benchmark figures of the building performance, whereas in the Detailed Design Stage the simulation focus will be, for example, on the design of the building services systems. Simulation tools should thus be flexible enough to provide the design team at every design stage with tools that enable them to carry out relevant analysis.

3.4.2 Include flexibility for future design trends or building technologies

The expectations from clients when commissioning a building design change over time. Recently, there has been a trend by some clients towards a requirement for non air-conditioned offices. Such buildings require a different design approach, the designers need to establish at early design stages whether or not their particular design concept can be cooled to the necessary levels by means of natural ventilation, what the required air change rates would be and in how far a heavy construction could contribute towards lower temperatures in the building – none of these evaluations would be part of the design of an air conditioned office building. If the trend towards non-air conditioning continues, the designer will need simulation tools that are suitable for carrying out the relevant simulation studies throughout the design process. Other design trends are likely to occur in the future and therefore it was seen as important that the SSDP is flexible enough to respond to such developments.

3.4.3 Produce simulation tools that will be accepted by designers

The contemporary building design process imposes much pressure on the design team members. There is therefore a risk that building simulation is seen as an additional 'burden' and not as a useful tool. An example of this would be at the Outline Design Stage, where designers have only limited time to create their design proposal – any tool used at this design stage will have to produce performance predictions in a fast turnover time. Such issues need to be reflected in the design of software tools for the SSDP.

3.4.4 Produce maximum results accuracy

The benefit of a simulation study for a designer depends on the accuracy of the performance predictions, which again depend on two main aspects: (1) the simulation engine of the simulation program, which performs the calculations and (2) the accuracy and detail of the model that was used in the simulation. The SSDP should be based on a state-of-the-art simulation engine that also allows a sufficiently accurate definition of the simulation model.

3.5 Introduction to the SSDP implementation concept

The previous section outlined the specification for the SSDP. This section introduces the implementation concept that was developed based on this specification. It is depicted in a diagram in Figure 3.3. The diagram shows that the same advanced simulation engine (ESP-r, [ESRU 2002]) is used throughout the design process, but with interfaces and performance prediction analysis customised to the different design stages. The ESP-r simulation engine (as described in section 2.4) is suitable for the various requirements outlined above: it is able to simulate a large number of design parameters, it provides the flexibility to adapt to the changing expectations that building designers might have from building simulation in the future and the detailed model definition in combination with the advanced simulation engine can produce a good performance prediction accuracy.

3.6 Discussion of and justification for the SSDP implementation concept

The literature suggests different approaches as to how to integrate simulation software into the building design process. CIBSE [1998 a] suggests two possible approaches: one applies simplified simulation tools at early building design stages and sophisticated ones at later design stages, the other uses sophisticated tools throughout the design process. Clarke [2001] suggests that it is more efficient to use a single simulation program throughout the building design process than to use a succession of tools. The following section describes the advantages of using the same simulation engine throughout the design process, followed by a justification of the approach.

3.6.1 Discussion of SSDP implementation concept

Communication is improved between the different design parties

It is desirable to bring together the different parties involved in the building design process because of the improvement that this can bring to the quality of the building. Kalay [1999] argues that the facilitating of collaboration between the various design professionals who are involved in the design process will represent convergence on a single, original goal – the use of computers to help designers assess the quality and implications of their design.

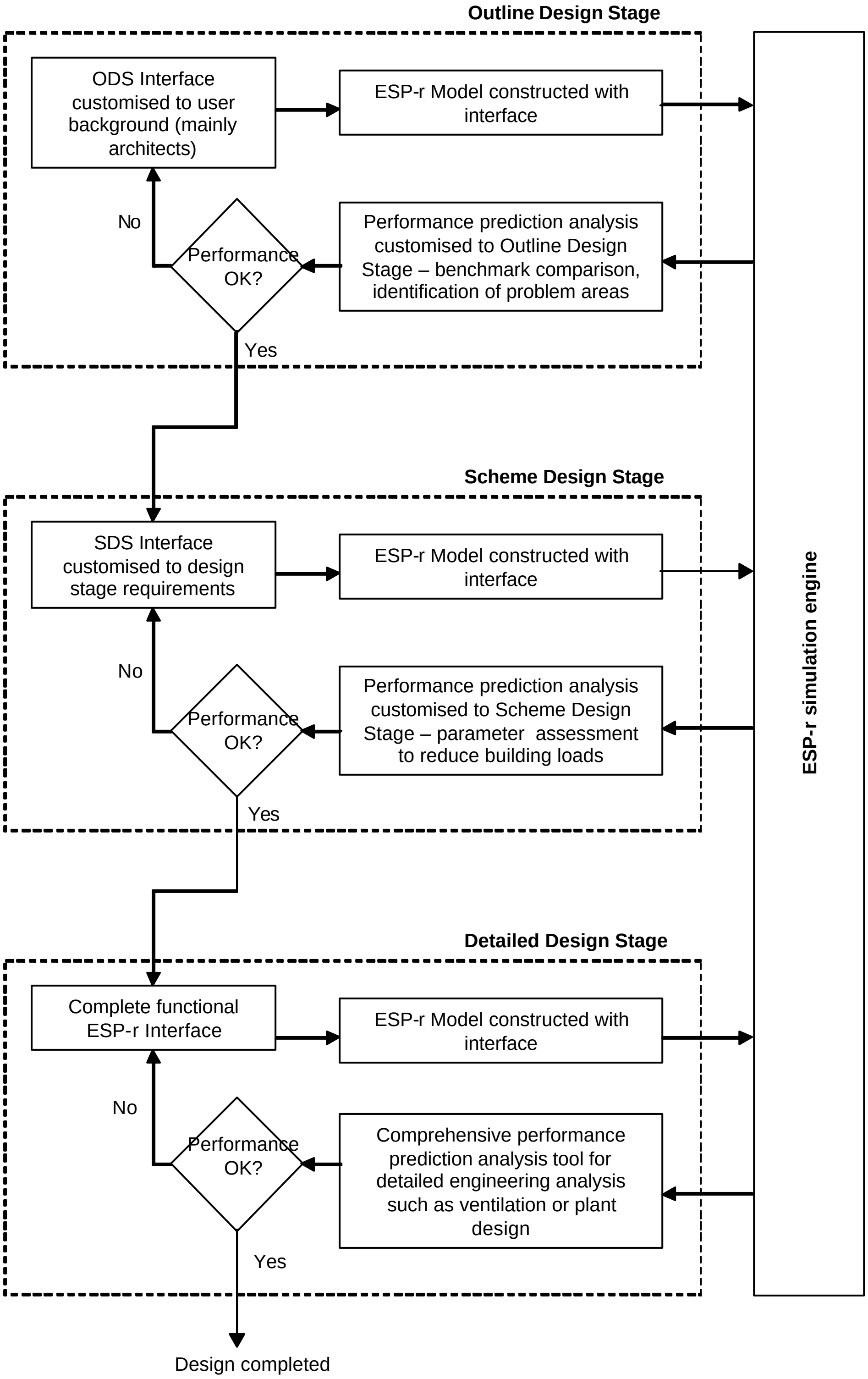


Figure 3.3 SSDP implementation concept

It can be argued that this communication is best achieved when the different design parties (especially architects and building services engineers) use the same simulation engine. As this enables building services engineers to work with a model previously created by an architect, either to extend it to carry out their own design work or to analyse in more detail a design aspect an architect would like to have evaluated in more detail. Discussions that can follow from such an exercise are assisted by the fact that both design parties will refer to a simulation model they are both familiar with. This helps to remove the decoupling of decisions made on mechanical systems and control from the early building design process [Hien et al 2000]. This was also emphasised by the DETR [1996] as an important design element:

> *"Services should form an integral part of the design concept of the building, not as a means of creating satisfactory internal conditions within a poorly designed building structure. It is important therefore that the Building Services Engineer is involved early on".*

Performance predictions are based on the same simulation engine

Because of validation issues that are involved in every simulation exercise (see section 2.5.6), the chance of a difference between predictions obtained from simulation and the performance of the real building remains. However, when the performance predictions are created with the same simulation program, differences will only be caused by variations in their simulation models and not by the use of different simulation engines, and will thus be valuable as comparators if not in absolute terms.

Developments of the simulation engine can benefit all design parties

Simulation programs undergo constant improvements, either by advancing the algorithm of an already integrated element or by implementing additional functionality. By using an advanced simulation engine throughout the design process, all design parties benefit from these developments. If different programs are used at the various design stages (e.g. the LT-Method at the Outline Design Stage and ESP-r at the Detailed Design Stage) enhancements only benefit certain groups of designers.

3.6.2 Justification for SSDP

In 2000, a training course was run for where architects were using the fully functional ESP-r interface. The course lasted three days and covered the tasks involved in the definition of a basic simulation model but also demonstrated how more complex simulation models are created. This gave the architects a fairly comprehensive overview over simulation exercises that can currently be carried out with an advanced simulation tool, but also skills and knowledge which is needed to perform such simulation exercises. An important conclusion from the course was that it is not advisable to integrate simulation into the building design process by simply making it available to all design team members. There are a number of reasons for this:

- The background of the different potential user groups of building simulation is very different (see section 3.3). The matter can be seen as analogous to the development of different CAD tools for the building design process: architects, structural engineers and building services engineers all require different user functions. The developers have not integrated them into one tool, but developed different versions for the different users.
- Architects, in particular, find it difficult to cope with the technical complexity required to enable them to evaluate different design options with an advanced simulation tool [Robinson 1996]
- The thesis has already highlighted the fact that the designer will want to evaluate different issues at different design stages. Integrating all of the user functions required into one tool will result in an over-complex system. Different users also need to be presented with performance predictions in different ways.

As a consequence of the conclusion derived from the ESP-r course (as described above) it was decided to continue to follow the idea of using the same simulation engine throughout the design process, but with interfaces, software functionality, defaults and results analysis tailored to the requirements of all three design stages and the corresponding user types.

3.7 Criteria for the selection of design parameters to evaluate with the SSDP

As part of the definition of the SSDP it was necessary to specify which design parameters to evaluate by means of simulation and at which design stage to carry out the assessment. This section discusses which parameters were included in the SSDP. These parameters are then allocated to the various design stages in section 3.8.

A decision had to be made about the design parameters that should be included within the modelling procedure. The selection was based on the following criteria:

- parameters that the designer will want to evaluate;
- parameters with important implications that the designer should be aware of, and

- parameters that are cost effective and that are already established in the built environment (e.g. photovoltaic panels have not been included because their payback periods can exceed the life span of a building).

Design parameters, especially for the first two considerations, will change with the project type. With a very energy efficient building design the design parameters would differ from a conventional building design. The discussion below relates to conventional building design, which was the main aim for the SSDP (rather than for example highly energy efficient building design that is not commercially viable).

The selection criteria listed above as well as the allocation of different design parameters to the various design stages as it will be described later in section 3.8 is the outcome of a considerable research effort over several months within the architectural company were the SSDP was developed which lasted several months. In an initial phase the author was introduced by senior members of the design team to the nature of the contemporary building design process. This knowledge was further increased by the author observing common design practise (monitoring progress and developments of design projects, attending design reviews, etc.). In the same period the author also introduced the designers to capabilities of contemporary advanced simulation tools. This initial research phase resulted in the development of a first prototype for a SSDP, which was then refined over time. An example for a later alteration of this prototype was the decision that air flow networks should mainly be applied at the Detailed Design Stage (initially they were fully integrated into the Scheme Design Stage).

3.7.1 Parameters the designer will want to evaluate

For a number of design parameters, designers will appreciate the potential benefits of use of simulation because they know it can influence the energy and environmental performance of the design. One example is the glazing area of a facade, which has an impact on the heat loss through the building envelope, solar radiation entering the building and natural light that is available. Architects are often uncertain about the implications of large glazing areas, and simulation can provide clarity [Baker and Steemers]. Another example is the impact of thermal mass on the summer performance in a building. All of these are issues that building designers are generally aware of, but are not currently able to evaluate in detail.

3.7.2 Parameters with important implications that the designer should be aware of

Sometimes it is useful to highlight the impact of design decisions to designers to emphasise possible performance implications. One example would be the quantification of heat loss caused by ventilation and how this compares with conductive heat loss. This could lead to the integration of a heat exchanger into the building design.

3.7.3 Parameters which are cost effective and established in the built environment

The design parameters that have been included in the selection are both cost effective and are already well established in the built environment as the SSDP should be applicable in the conventional building design process.

Cost effectiveness

Only cost effective building components have been included into the SSDP. Building integrated electricity generation such as photovoltaic (PV) panels or ducted wind turbines are for example not cost effective and have hence not been considered. This situation could change in the future with the development of new technologies or the introduction of substantial funding by the government. In that case such parameters would need to be taken into account.

Established in building industry

It was decided to consider only building techniques in the SSDP that are established in the building industry in order not to overcomplicate the procedure. The introduction of simulation in combination with additional design considerations as new elements could cause resistance caused by the increased complexity of the decision making.

It could be argued that upcoming (and hence non-established) technical developments *should* be integrated into the simulation approach, e.g. the utilisation of wind energy in the built environment because such inclusion would mean that simulations could have educational benefits by highlighting benefits to the designer. However, it was concluded that the above argument was of greater importance for the successful implementation of the SSDP.

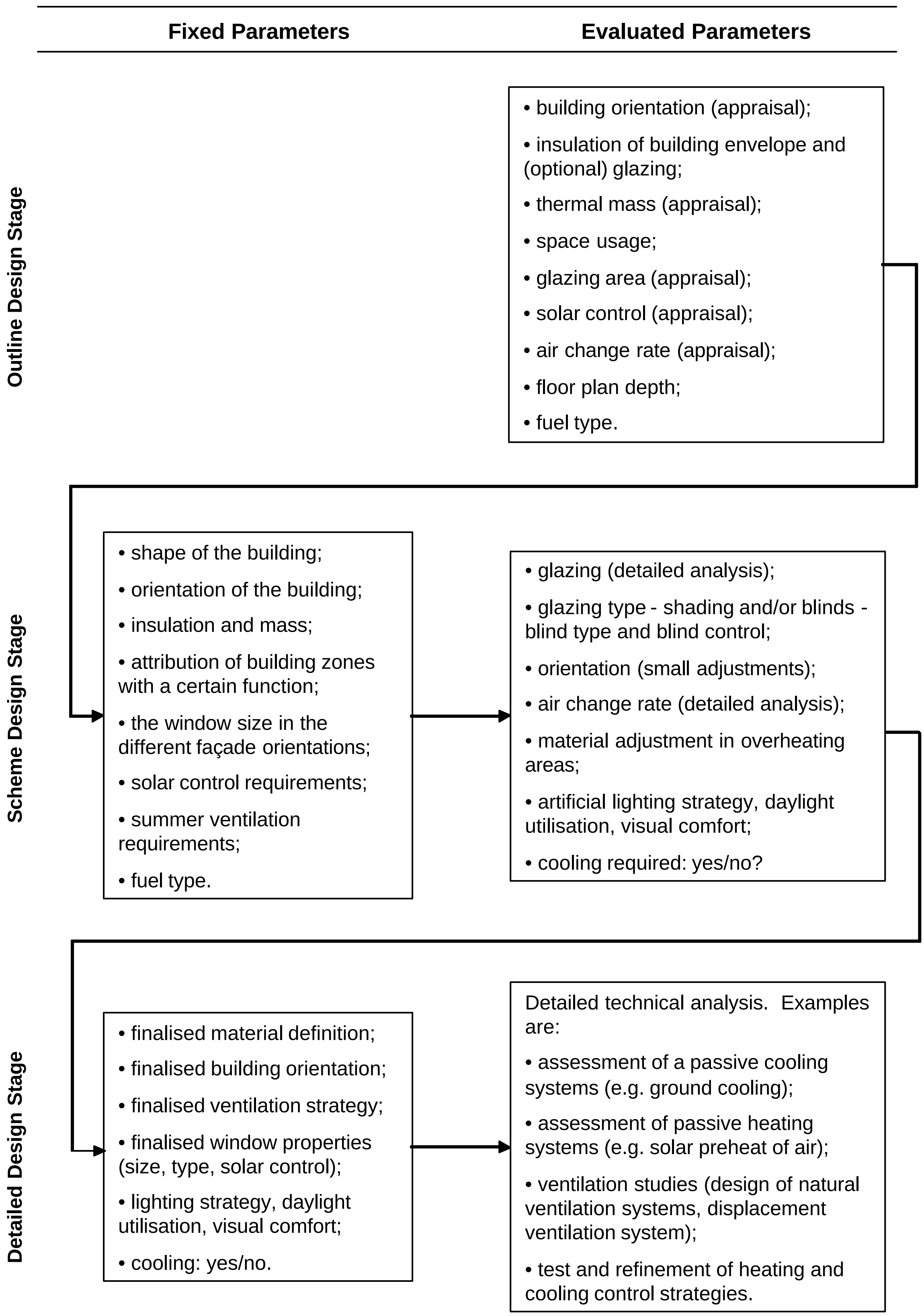


Figure 3.4: Design parameters to be evaluated at the various building design stages

3.8 Design parameter evaluation at different building design stages

Figure 3.4 displays the different parameters identified as relevant for an evaluation with simulation tools at the different building design stages. The following sections will discuss these choices in more detail. The process how the parameter classification was derived was described in section 3.7.

3.8.1 Parameters included in the Outline Design Stage

Table 3.2 lists design parameters that were identified as relevant for an evaluation at this design stage (see section 3.7). In the next sections, the text discusses the content of the table in more detail.

Design parameter	Reason for appraisal
Building orientation (appraisal)	Orientation might be altered in response to site conditions or in order to improve the energy or environmental performance.
Insulation of building envelope and (optional) glazing	Construction types are normally established at an early design stage; glazing might already be 'fixed' to double-glazing.
Thermal mass (appraisal)	Early design decisions about constructions also affect thermal mass of building.
Space usage	The location of the different functional zones in the building is an important consideration at the Outline Design Stage.
Glazing area (appraisal)	Decisions about glazing areas are mainly made at the Outline Design Stage and implications of these choices should be emphasised to the designer.
Solar control (appraisal)	In certain design projects it might be important to give the designer an understanding for potential improvements of the building performance by applying solar control.
Air change rate (appraisal)	In certain design projects it might be important to give the designer an understanding for potential improvements of the building performance by changing ventilation rates.
Floor plan depth	With the specification of the building geometry the designer also establishes floor plan depths for a building. It is important to indicate implications for building performance.
Fuel type	Fuel types are often established at early building design stages and affect the energy cost and emissions from the building.

Table 3.2: Design parameters evaluated at the Outline Design Stage (summary of following discussions)

Building orientation (appraisal)

There can be different reasons for evaluating different building orientations:

- An initial appraisal has resulted in a number of design concepts with different building orientations.
- The designer intends to rotate a building to improve performance parameters such as side access or fire regulations.

- The designer considers a change of the building orientation as a result of a poor building performance identified in a simulation run (e.g. rotate spaces that overheat out of the sun).

How far the orientation of the building can be altered as part of a specific design project will depend on design constraints. The site may only allow one orientation for a building or the architect might not be prepared to consider another orientation, perhaps in order to direct a certain building section with a prestigious façade towards a certain orientation. These constraints can limit potential orientations to only a few possibilities[1].

Insulation of building envelope and (optional) glazing

There are a number of reasons why the construction types used in the building (and hence the U-Value of the building envelope) are often established at the Outline Design Stage:

- To establish the cost of a building it is necessary to have an understanding of the constructions used.
- The construction time depends on the building materials used. In many building projects this is important, so construction type will be selected at an early design stage.
- The finishing of the building envelope influences the aesthetic appearance of the building and aesthetics are important considerations of the ODS. The finishing will depend on the materials used and will therefore also have to be considered.

The building insulation is an important parameter that influences the energy performance of a building, as already indicated earlier (section 1.2) with respect to the Building Regulations. Whether to also assess the U-value of the windows will depend on the design aim. In a conventional building design the client will ask in most cases for double-glazing. If the intention is to design a low energy building, high insulation glazing should be taken into account.

[1] Some research aims at establishing a building orientation by applying optimisation technique towards limited parameters. For example, Klemm et al [1999] do this with respect to the air flow around a building. The numerous issues that affected decisions about the building orientation make the applicability of the approach questionable.

Thermal mass (appraisal)

The massing of the building is also affected by early decisions related to the building construction. The thermal mass can significantly influence summer comfort within the building. Again, a number of considerations will influence the design decision. Lightweight partitions are cheaper than brick partitions and also offer a higher degree of flexibility for future changes of the room layout. Suspended ceilings are often used for the building services. Despite these disadvantages a designer might still chose a heavyweight construction if simulation has illustrated the benefits.

Space usage

A significant part of the design decisions made at the Outline Design Stage is the location of different functional zones in the building. This can be influenced by operational (distance between two different functional zones of a building) or external conditions (place the ward section of a hospital so that the occupants have a nice view towards the outside). A change in space usage can influence both energy consumption and comfort of a building. For example, positioning a building zone with high internal gains in a south or west-orientated building section can increase summer overheating problems, which should be addressed by the design team. The designer might then deliberately change the distribution of different space functions to improve the performance of a building. Enabling a designer to assess these implications can support the decision process and space usage was therefore included as a parameter in the Outline Design Stage[1].

Glazing area (appraisal)

Glazing area is an important issue for architects, to a large extent because it is a major means of influencing the aesthetics of a building. Prestigious fully glazed entrance halls or fully glazed facades, for example, are now commonly found in the built environment. Glazing decisions are mostly made at the Outline Design Stage and their impact on the design should then also be addressed. DDSS such as the LT-Method [Baker and Steemers] assist designers with optimisation of building glazing ratios.

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[1] The distribution of the different space functions within the building is generally a major consideration at the Outline Design Stage. It involves considerations ranging from distance between related rooms to fire strategies. This has resulted in simulation tools that try to address these issues [Leusen and Mitossi 1998].

Solar control (appraisal)

At the Outline Design Stage the designer will normally not carry out a detailed appraisal of different solar control options. However, it might still be feasible to evaluate the general potential of solar control to improve summer comfort conditions. This should be carried out in a pragmatic way, e.g. by enabling the designer to incorporate an advanced solar control mechanism such as efficient external blinds to give an understanding of the potential of applying solar control. With this approach the designer obtains a general understanding in how far solar control can or cannot enhance the summer performance of the building (solar control might actually in some cases not be useful because cooling loads are produced for example by internal heat gains). The exact design of the solar control will be tested and specified at later design stages.

Air change rate (appraisal)

Summer comfort is, to a significant extent, influenced by the air change rate of the building. Hence an analysis should be undertaken of the impact of the air change rate on the summer performance of the building. The simulations are at this stage undertaken by means of different fixed ventilation rates; detailed analysis using air flow networks is not applied. Two design team members benefit from this simulation:

- The architect who gains an understanding how far a design can provide required comfort conditions by enhanced natural ventilation in combination with the building form and fabric;
- An HVAC expert who can evaluate whether the required ventilation rate can be achieved in the proposed building design.

Floor plan depth

Floor plan depth is another important design parameter at the Outline Design Stage, and the implication of the choices made should be made clear to the designer. Decisions made have influence on

- heating and cooling loads;
- the natural light in the building;
- energy requirements for mechanical ventilation.

The floor plan depth, and hence the ratio of the building volume to the external surface area, affects both the heating and cooling load of the building. A compact building design reduces the external surface area and hence the conductive heat loss of the building. In addition, uncontrolled infiltration does not occur in areas located in the centre of the building. Rooms in the core of the building will also not receive any direct solar heat gains. The cooling load that needs to be provided by the air conditioning plant can thus be reduced to the cooling of ambient air and the removal of internal heat gains but not solar gains.

Daylight is only available at the perimeter of a building. A number of parameters that influence the daylight availability in the building are often not determined at this design stage. Examples are the colour of surface finishes, the window shape and location in external wall. Making a prediction of the daylight factors using simulation will therefore provide results with some degree of uncertainty, but the information is still of significance for later design stages and the general performance of the building and should be communicated to the designer[1].

Energy requirements for mechanical ventilation is another factor affected by the floor plan depth. Deep core buildings can have significantly higher energy requirements caused by the need for mechanical ventilation.

Fuel type

The fuel type used in the building can have significant implications for the energy cost and emissions caused by a building. This selection of a fuel type for a building also often takes place at early building design stages and should therefore be included in the appraisal at the Outline Design Stage.

3.8.2 Parameters included in the Scheme Design Stage

Table 3.3 lists design parameters that were identified as relevant for an evaluation at this design stage (see section 3.7). In the next sections, the text discusses the context of the table in more detail.

Glazing (detailed analysis)

Because of lack of information and time constraints at the Outline Design Stage decisions made related to the glazing area tend to be general. The Scheme Design Stage offers the opportunity to assess glazing issues in more detail. Possible assessments are:

[1]Assessments at the Outline Design Stage will normally neglect visual comfort. The designer will not be able to assess other parameters such as glare or visual comfort at a workspace until a later point in the design process, when design parameters such as floor finishing type and location of occupants in the building have been established.

- Size and position of a window with the objective of utilising natural light and ensuring visual comfort.
- Determination of the reduction in glazing area locally to overcome an overheating problem that was identified in a certain area of the building. This could, for example, be the case in an IT room with significant internal heat gains.

These assessments will require the use of both thermal and lighting simulation tools.

Design parameter	**Reason for appraisal**
Glazing (detailed analysis)	The designer might want to change the local window size in response to a performance problem. Another general consideration is the window format and position.
Glazing type - shading and/or blinds - blind type and blind control	Thermal and visual comfort as well the air conditioning requirements can be influenced by changes of these design parameters.
Orientation (small adjustments);	Although the general building orientation is fixed it is still possible to carry out small adjustments in response to an inadequate building performance.
Air change rate (detailed analysis)	The user can carry out a more detailed assessment of the ventilation scheme itself (wider range of ventilation options, night purge) or assess it in combination with other design parameters (e.g. different solar control options).
Construction adjustment in overheating areas;	The designer can change the thermal mass of the building locally (e.g. in an IT room) to provide a better heat sink.
Artificial lighting strategy, daylight utilization, visual comfort;	Glazing and solar control design choices will affect the lighting strategy for the building.
Cooling required: yes/no?	At the end of the Scheme Design Stage the designer will have an understanding if the building requires cooling.

Table 3.3: Design parameters evaluated at the Scheme Design Stage(summary of following discussions)

Glazing type - shading and/or blinds - blind type and blind control

All of the parameters discussed in this section relate to visual and/or thermal comfort and also potentially to air conditioning requirements. They will be used to address problems that have been identified earlier at the Outline Design Stage or in studies at the Scheme Design Stage.

A large number of advanced glazing systems have been developed in response to visual or thermal comfort problems that occur in a building. Blinds or shading elements are another way to reduce or remove visual or thermal comfort problems and can be applied in combination with advanced glazing systems. Their control can vary from occupant operation to advanced control systems that respond to ambient or internal conditions. The position (internal, mid or external) and design (cloth, metal fins, etc.) of the blind system can also vary. By applying simulation the designer can compare the impact the different systems can make on the building performance.

Orientation (small adjustments)

The basic orientation is fixed at this design stage. However, in some cases there is still scope to make minor adjustments to the orientation (by say 5/10º [1]). These adjustments can be useful to improve the building performance, e.g. in terms of summer comfort. One example could be west orientated rooms with an overheating problem: turning the building (and hence these rooms) by 10º towards the north will reduce the intensity of the incident solar radiation.

Air change rate (detailed analysis)

With the SSDP an appraisal of the impact of the ventilation rate may already have been undertaken at the Outline Design Stage. Now at the Scheme Design Stage the designer will be able to undertake a more detailed assessment. This can focus on the ventilation scheme itself (assessment of a wider range of ventilation rates, night purge), or the assessment of the correlation of changes in the ventilation rates with other factors such as advanced glazing systems, blinds, shading elements or the mass of the building.

In many cases this assessment will still be based on fixed ventilation rates that are defined for the simulation model and not on an air flow network. This is sufficient if the engineer designing the ventilation system is able to predict whether or not it will be possible to design a system that will provide the defined ventilation rates. However, in other cases it might be necessary to carry out an assessment using an air flow network. It is not possible to define at what design stage air flow simulation should be applied within the building design process.

Construction material adjustment in overheating areas

If the designer has opted for a lightweight construction it is maybe still possible to change this locally in overheating areas to a more massive construction in order to provide a better heat sink in order to improve the comfort conditions. Lightweight constructions are

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[1] This 'change by 5/10º' was a design consideration that was mentioned several times by different designers. Generally it could be questioned that such small changes significantly affect the performance of the building, but because of the importance the designer gave to this consideration it was still included into the SSDP.

generally cheaper and quicker to construct, therefore adopting the approach outlined above will ensure that heavyweight construction is only used if required.

Artificial lighting strategy, daylight utilisation, visual comfort

A number of parameters specified at the Scheme Design Stage also have an impact on the lighting energy consumption of the building. After having specified these parameters the designer has sufficiently detailed information to design artificial lighting strategies, daylight utilisation strategies and to ensure visual comfort, therefore these design aspects should be addressed at this phase of the design.

Cooling required: yes/no?

Many of the design criteria listed above are intended to improve the summer conditions in a building. If it is found that these alone are not sufficient to provide required comfort conditions it will be necessary to apply cooling to the building. By this stage, a designer obtains an indication of whether or not this is necessary.

3.8.3 Parameters included in the Detailed Design Stage

At the Detailed Design Stage, the building design is worked through in detail. Any simulations undertaken will be for technical reasons, for example advanced thermal or visual assessments of the building. Examples of such simulation projects are:

- assessment of a passive cooling systems (e.g. ground cooling);
- assessment of passive heating systems (e.g. solar preheat of air);
- ventilation studies (design of natural ventilation systems, displacement ventilation system);
- test and refinement of heating and cooling control strategies.

However, simulation at the Detailed Design Stage is currently not limited to such advanced exercises. It is also used to evaluate advanced glazing systems, shading elements and blinds. This contradicts the approach that has been presented on the previous pages. The reason is that in current practice simulation is often used for performance confirmation of a nearly completed building design. For this, the assessment of solar control features is undertaken to evaluate how a design problem that has been identified at this late design stage can be resolved. By using the SSDP, these problems should be identified earlier, making it easier for the designer to respond before the design is fixed. With regards to the above example, studies of advanced glazing systems, shading elements and blinds are therefore not carried out at the *Detailed Design Stage* but already at the *Scheme Design Stage*.

3.9 Comparison with other parameter classifications

The main aim of the research carried out in the previous sections (3.7, 3.8) was to ensure that the design parameter classification developed as part of the SSDP was consistent with the requirements of the architectural practice that formed the test bed for the application of simulation within the building design process (and especially at early building design stages). This part of the research was important because any conclusion regarding the applicability of simulation within the building design process needed to be based on a structure were the optimal application of the tool (support of relevant design decision at the various design phases) was ensured.

However, it was also found of interest to evaluate to what extent the outcome of the research is also valid for the building industry in general. This section therefore compares the parameter selection with other published classifications.

The approach developed was compared with two other approaches that address energy and environmental issues within the building design process: the CIBSE Energy Efficiency Guide [CIBSE 1998 b] and the Good Practice Guide “Environmentally Smart Buildings” [DETR 1999]. The former gives general advice on how to work towards an energy efficient building design, the latter proposes low energy measures for different design stages considering construction cost. A direct comparison was to a degree affected by the fact that both approaches only distinguish between Sketch Design Stage and Specific Design Stage.

The CIBSE approach focuses at the Sketch Design Stage on the following parameters:

- building shape,
- thermal response,
- insulation,
- windows,
- ventilation strategy,
- daylight strategy,
- plant and control,
- fuels,
- metering.

Metering is not really related to the application of simulation in the building design process. Building shape, thermal response, insulation, plant and control, and fuels are addressed in the

SSDP during the Outline Design Stage. Windows, ventilation and daylight are also addressed, but the CIBSE Guide suggests for the Sketch Design Stage a more detailed evaluation than was suggest for the SSDP. This includes shading elements and blinds when designing the windows and the evaluation of daylight factors considering surface properties and window location. The experience during the research indicated that these design parameters would often not be specified at the Outline Design Stage. An explanation for the extended parameter evaluation of the CIBSE Guide could be the fact that it is published by building services engineers, and hence design considerations related to the architectural work were summarised as Sketch Design Stage. Sketch Design Stage could be understood to be what RIBA defines as the Scheme *and* Outline Design Stage, because it is the phase where the building services engineer conventionally makes only limited contributions. The second design phase in the Guide is the called Specific Design Stage and evaluates mainly building services issues. This corresponds with the Detailed Design Stage of the SSDP.

The Best Practice Guide suggests for the Sketch Design Stage the following parameters:

- orientation,
- glazing area,
- external blinds,
- painting of wall,
- removal of suspended ceiling.

The guide is not ideal as a comparator because it is not a design adviser but gives suggestions for quantity surveyors who are not directly involved in the design decision making process. However, at the Sketch Design Stage it includes mainly considerations that the SSDP addresses. For the Specific Design Stage it focuses on building services issues, but it also considers changes to the insulation level.

The similarities between the three approaches allow the conclusion that the design parameters specified for the SSDP are not substantially different to what could be called the ‘normal’ design approach found in Great Britain.

3.10 Implementation and focus chosen

In addition to the development of the SSDP structure, the research also had the aim of developing tools that would support its implementation into the design process. The following section discusses the focus chosen for the research into these tools. Table 3.4 lists the main aspects that relate to the application of advanced building simulation in the design process and by designers by summarising findings described in previous parts of this thesis.

The focus chosen for the development of prototypes (which is highlighted in the table) is discussed and justified in the sections that follow the table (3.10.1 to 3.10.3).

Design Stage	Model Creation	Performance Prediction Analysis
Outline Design Stage	Typical users identified (architects) find it difficult to use advanced simulation programs.	Performance prediction analysis is difficult for an architect.
Scheme Design Stage	Does not cause major difficulties to a simulation expert but time consuming in case of in-depth analysis.	Complex if applied as proposed in the SSDP. It is important to obtain an in-depth understanding of reasons behind a building performance and to compare different reference cases.
Detailed Design Stage	Normally more challenging than simulation exercises at the Scheme Design Stage, but possible for a simulation expert.	Depending on the simulation study ranges from easy to complex, tedious and time consuming.

Table 3.4: The application of dynamic building simulation at different design stages
(indicates development of prototypes in this research)

3.10.1 Outline Design Stage

Building simulation is currently used a lot more at the Scheme and especially Detailed Design Stage rather than the Outline Design Stage. However, design decisions at the Outline Design Stage can have major implications on the energy consumption and comfort conditions of buildings. It is therefore desirable to integrate dynamic building simulation into this design stage. As discussed in chapter 2, the difficulty of using simulation is a major barrier for the uptake of the technology at this design stage. The development and testing of a prototype was therefore an important part of the research.

3.10.2 Scheme Design Stage

Creating a simulation model that can be used to assess the parameters identified for the Scheme Design Stage is not a problem for a simulation expert, but difficult for a non-simulation expert like an architect.

Research into a tool that could be operated by architects at the Scheme Design Stage would have been another possible direction of research. However, for the reason stated above it was decided that it was important to first integrate simulation into the Outline Design Stage. The experience gained from this can then be used as a basis for additional software developments to enable simulation at later design stages.

3.10.3 Detailed Design Stage

At the Detailed Design Stage experts already apply dynamic building simulation. They use the software on a regular basis and normally have additional background knowledge of technical aspects of a simulation exercise (pressure coefficients of air flow network, plant control issues, etc.), hence research was found to be of lesser priority.

A different view was taken for the results analysis at this design stage. The analysis of performance predictions obtained is often carried out by examining the behaviour of a building over short periods. Performance predictions obtained from longer simulation runs[1] are then mainly utilised to obtain key performance data such as annual energy consumption and frequency binning of summer temperatures. This has the consequence that the person carrying out the simulation exercise might not have a complete understanding for the characteristics of the building. As a result, efforts to improve a building design are often made on the basis of trial and error rather that on informed decision making. The director of a building simulation company estimated than this is the case more than 50% of the times when simulation is applied in the building design process [Ho 1999]. For this reason it was decided to undertake research into how the quantity and quality of the information obtained from a simulation study could be increased.

3.11 Closing remarks

The chapter described research into a simulation supported design process (SSDP), a first step towards the integration of simulation into the building design process. It was found that the potential role of simulation during the SSDP would differ according to the design stage, ranging from a quick evaluation of fundamental design decisions at early design stages carried out by architects to detailed technical studies at late design stages performed by engineers.

The chapter also described an SSDP implementation concept, which uses the same advanced simulation engine throughout the design process, but with interfaces and performance analysis customised to the different design stages. In a discussion of the concept it was stated that it would enhance the communication between different design parties, that all the performance predictions are based on the same simulation engine and that developments of the simulation engine can benefit all design parties.

The development of an SSDP also requires the definition of design parameters to be evaluated at the various building design stages. The research selected parameters that were

[1] The issue of the length of the simulation period itself is discussed later in Section 5.5.3.

cost effective and established in the built environment since the SSDP should be applicable in the conventional building design process. The outcome of the research was compared with two other design parameter classifications and an acceptable agreement was observed.

A general comment regarding the research described in this chapter is the fact that it was mainly carried out in collaboration with designers of one architectural practice. This provided the advantages as outlined in section 1.7 (work with people who have a good understanding of design process, carry out a detailed and focused study), but it also bears the risk of being too limited. As a result one of the suggestions for future work is to test the SSDP in other design practices (see section 8.4.1). However, the research approach had the significant advantage that a concept could be tested *and* implemented within the same environment. It was hoped that this would limited the risk of trying to implement ill-fitting an approach into an architecture company and draw wrong conclusions regarding the general applicability of simulation within the building design process.

The chapter also discussed the implementation prototypes chosen as part of this research project. It was decided to focus on the model creation and performance prediction analysis at the Outline Design Stage as well as performance prediction analysis at the Detailed Design Stage. The focus on the Outline Design Stage was justified by the fact that design decisions at early design stages have the biggest implications on the energy and environmental performance of the building. Attention to the performance prediction analysis at the Detailed Design Stage was motivated by the fact that this analysis currently often only focuses on short simulation periods, hence potentially preventing the designer from getting a complete understanding of the behaviour of the building.

The next chapter introduces the ODS-Interface, which was developed with the aim of enabling non-simulation experts to create detailed simulation models at early building design stages. It is based on research findings described in this chapter regarding the application of simulation at the Outline Design Stage and was important in order to achieve the research objective which was specified in section 1.7 (and justification in section 3.3.1): The implementation and monitoring of the use of simulation at an early building design stage in an architectural design practice.

References

Baker N V, Steemers K, “The LT Method, Version 2 – an Energy Support Tool for Non-domestic Buildings” (The LT Method was Developed by the Martin Centre for Architectural and Urban Studies, Cambridge and is Available from the Royal Institute of British Architects, RIBA).

CIBSE a (Chartered Institution of Building Services Engineers), “Building Energy and Environmental Modelling”, CIBSE Application Manual AM 11, CIBSE, 1998.

CIBSE b (Chartered Institution of Building Services Engineers), “Energy Efficiency in Building”, CIBSE, 1998.

Clarke J A, “Energy Simulation in Building Design”, Butterworth-Heinemann, Oxford, 2001.

Clarke J A, Cockroft J, Conner S, Hand J W, Kelly N J, Moore R, O’Brien T, Strachan P, “Control in Building Energy Management Systems: The Role of Simulation”, Proceedings Building Simulation 01, Rio de Janeiro, pp 99-106, 2001.

Clarke J A, Personal Communication, 2000.

De Wilde P, Augenbroe G, van der Voorden M, “A Strategy to Provide Computational Support for the Selection of Energy Saving Building Components”, Proceedings Building Simulation 01, Rio de Janeiro, pp 653-660, 2001.

De Wilde P, Personal Communication, 2001.

DETR (Department of Environment, Transport and the Regions), “Briefing the Design Team for Energy Efficiency in New Buildings”, Good Practice Guide 74, 1996.

DETR (Department of Environment, Transport and the Regions), “Environmentally Smart Buildings – a Quantity Surveyor’s Guide to the cost Effectiveness of Energy-efficient Offices”, Good Practice Guide 274, 1999.

ESRU, “ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series”, University of Strathclyde, Glasgow, 2002.

Hien, W N, Poh L K, Feriadi H, “The Use of Performance-based Simulation Tools for Building Design and Evaluation – a Singapore Perspective”, Building and Environment, Volume 35, pp 709-736, 2000.

Ho C, Director of Consultancy Company “Building Simulation”, Personal Communication, 1999.

Kagioglou M, Cooper R, Aouad G, Hinks J, Sexton M, Sheath D, "Final Report: Generic Design and Construction Process Protocol", Published by the University of Salford, 1998.

Kalay, Y E, "The Future of CAAD: From Computer Aided Design to Computer Added Collaboration", Proceedings of the Eighth International Conference on Computer Aided Architectural Design Futures, Atlanta, 1999.

RIBA (Royal Institute of British Architects), "Architect's Job Book", RIBA Publications, 1995.

Robinson D, "Energy Model Usage in Building Design: a Qualitative Assessment", Building Services Engineering Research and Technology, Vol. 17, No. 2, CIBSE, pp 89-95, 1996.

CHAPTER 4

SIMULATION MODEL CREATION AT THE OUTLINE DESIGN STAGE

4.1 Introduction

The previous chapter introduced the different building design stages and the SSDP which aims to improve the use of simulation as a DDSS throughout the building design process. This chapter describes a software tool that was developed with the aim enabling the application of dynamic building simulation at the Outline Design Stage by non-simulation experts – the ODS Interface.

The research into the ODS-Interface was again carried out over a longer period in close conjunction with architects. Initially dummy interface(s) were developed in response to deficits architects had identified from their experience in using an advanced simulation tool (e.g. difficult to navigate through program, data definition like heating setpoint specification exceeds knowledge of architects). In addition was the design of the dummy interface influenced by views the author had taken during the research of the SSDP on ways how the applicability of simulation by architects could be enhanced. The dummy interfaces were then tested by several designers and refined. This initial research phase took two months. This was followed by an eight month period were a first working interface was developed. During training of architects and the use of the tool on project the benefits of additional refinements became apparent, which were then incorporated into the tool. This second phase has for example resulted in a wider range of options in the definition of local surface properties.

4.2 Specification

The last chapter identified different issues relevant to the use of simulation at the Outline Design Stage. Simulation tools would (1) need to be usable by non-simulation experts and (2) allow a quick and accurate model definition. Taking these aspects into account, a requirement specification was derived as follows.

4.2.1 Constrained interface

The ODS-Interface needs to be based on a constrained interface that does not provide all of the functionalities of the full ESP-r system. There are two main reasons for this:

- Only design parameters identified in the SSDP as feasible for the Outline Design Stage were required to be assessed by the software.

- A significant number of simulation studies that are possible with the full ESP-r system can only be carried out by simulation experts. Since the typical user of the ODS-Interface is envisaged as not having such expertise it was regarded as important to include only simulation exercises that a typical user of the ODS-Interface could readily accomplish.

4.2.2 CAD-link

Architects in the architectural design practice that was used as a testbed in this research gave high priority to the application of CAD (Computer Aided Design) tools in conjunction with simulation (i.e. Webster [2000] and Cafferty [2000], both senior members of the architectural company, who were both heavily involved in the research of the SSDP and the ODS-Interface). They argued that they were familiar with the user functions of the CAD tool, allowing a quick definition of the model geometry. A second benefit of using a CAD tool is that the architect can use existing drawings to define the model geometry, rather than printing out the drawing and determining the building dimensions from a hard copy. This increases input speed and reduces the likelihood of input errors. The lack of CAD-integration of many simulation programs was also identified in research by Hien at al [2000], Donn [1997] and Robinson [1996].

4.2.3 Guided input procedure

The typical user of the ODS-Interface is unlikely to use the software on a daily basis. It was therefore considered essential to give the user as much guidance as possible when specifying the model, which led to the decision to base the model creation process on the wizards that are typically invoked when installing new computer software. A similar approach is used by Energy 10 [NREL 2002] and was identified in Robinson [1996] and Pohl et al [2000] as a necessary development.

4.2.4 Support databases

In the initial phase of the research, architects who attended a training course of the full ESP-r system regarded the detailed and time consuming data definition required when creating a simulation model as a problem if they were to use the program on a regular basis. Hien at al [2000] identify in their research the very extensive data input as the main limitation of current simulation tools. Donn [1997] and Robinson [1996] also state that the provision of pre-defined support databases is a necessary and required improvement for sustained tool use. In consequence recently developed simulation programs provide support databases [LBNL 2002, NREL 2002].

4.2.5 Link to other design aspects

As stated previously, energy and environmental issues typically have only limited consideration in the building design process. Therefore, to encourage the integration of simulation into the building design process it was considered important to structure the ODS-Interface in a way that allows the integration of additional, non-simulation related functionality into the software. Figure 4.1 illustrates the concept as seen by the author. The general belief in the benefits of such links has already resulted in research efforts such as the COMMIT Project [Cooper at al 2000].

A link to cost calculations was identified from the outset of the project as a valuable function to be integrated into the software. This allows architects to evaluate energy consumption figures obtained from the simulation exercise in the context of additional initial investment cost against savings over the building lifetime, payback periods, etc. Such financial consideration has become more important with the increase of PFI/PPP projects in the built environment, where the investor paying for the construction of a building is also responsible for its maintenance and running cost.

It can be expected that current developments in the construction industry will lead to the addressing of cost considerations other than construction cost during the building design process. The construction industry has already started looking at buildings using a holistic approach that addresses all aspects of the building life cycle [CIBSE 2000], including the maintenance of the building, energy cost, etc.

The integration of these functions into a simulation program is made easier by the fact that simulation models are based on the concept of zones and surfaces – entities that are required to undertake costing exercises.

4.3 Introduction to the ODS-Interface

Figure 4.2 displays the ODS-Interface and the two software tools it utilises. One is the full ESP-r simulation engine which produces the performance predictions, the other one the CAD tool which is used for the geometry definition of the simulation model. The Figure also shows the project database and support databases which are maintained by a Database Management System.

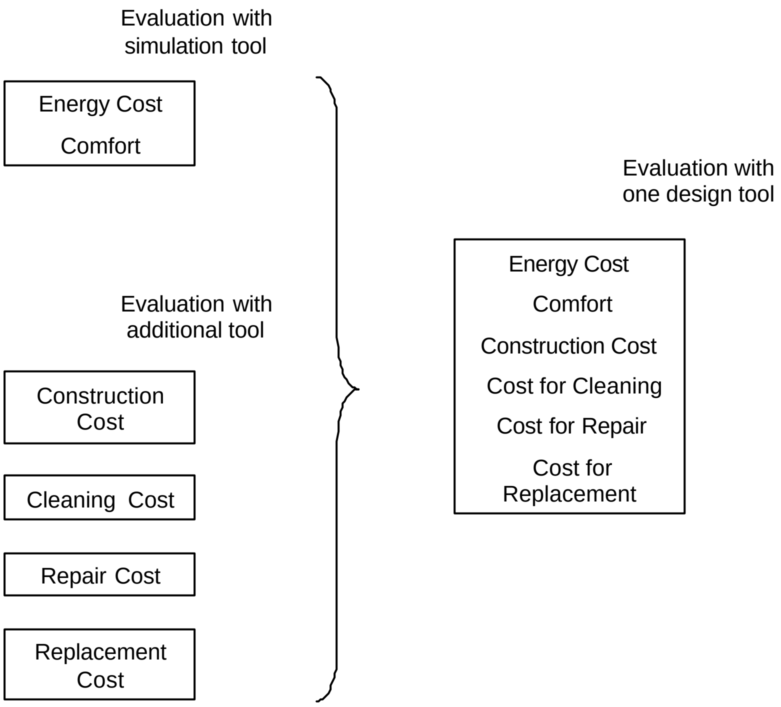


Figure 4.1: Supporting the integration of building simulation into the Outline Design Stage by linking it to other aspects of the building design process.

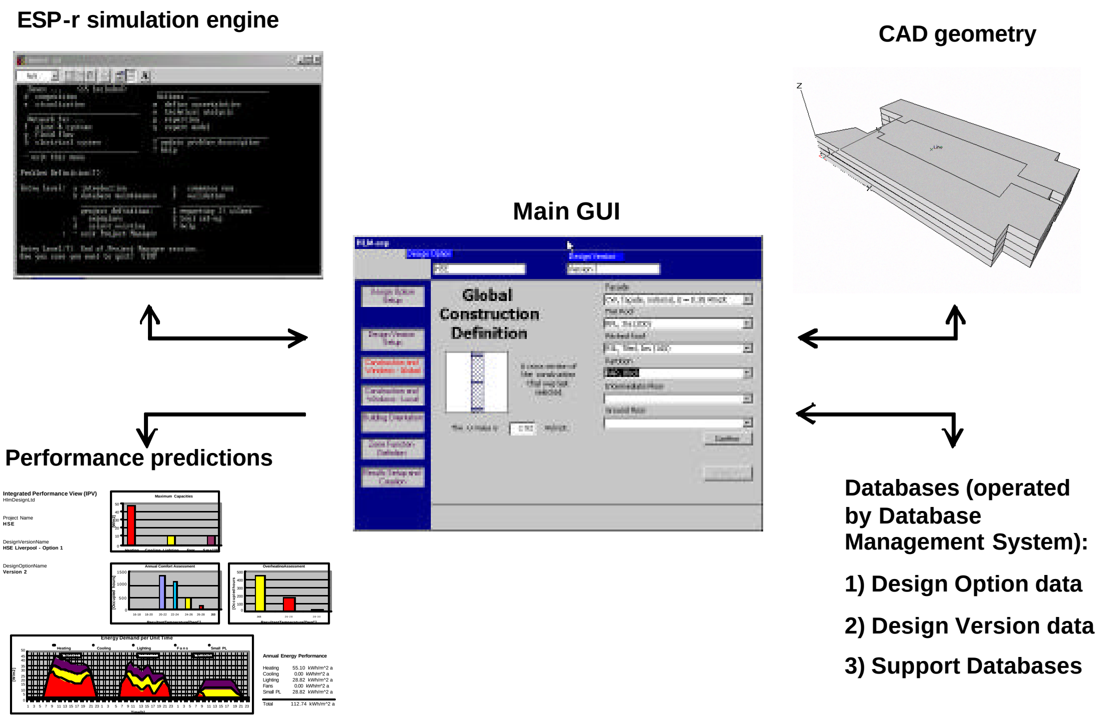


Figure 4.2: Main components of the ODS-Interface and software tools utilised

The following sections describe in detail several aspects of the ODS-Interface:

1. Database Management System (DBMS) in the ODS-Interface;
2. the data model developed for the ODS Interface;
3. the use of CAD in conjunction with the ODS-Interface;
4. support databases of the ODS-Interface;
5. the guided input procedure of the ODS-Interface;
6. QA issues in the context of the ODS-Interface.

4.4 Advantages of applying a Database Management System (DBMS)

Building simulations involve the frequent processing of data and require the following functions:

- Standard functions such as copying or deleting of data. This often includes the processing of data sets that are linked to a data item to be deleted or copied. An example is the deletion of all alternative models (in the ODS-Interface called "Design Versions") that have been created based on a certain geometry definition (in the ODS-Interface called "Design Option").
- Quick retrieval of datasets. This can include data items that relate to very different entities, such as all the hospital design versions that have an energy consumption below a certain level.
- Advanced simulation programs have different data access levels: support databases are normally only editable by an administrator, but users can still view and use them to attribute their simulation models. A simulation model will often only be accessible to the person who created it. However, especially when applying simulation within building design practice, flexible, multiple user access to the simulation model might be required. Some users might only be allowed to view a certain simulation model; others can also copy or edit the data.
- Storage of the data in a manner that allows simultaneous data access for several users of the simulation program.

In most simulation tools such functions have been hard-coded into the software or are carried out with the operating system within which the program is running. However, many of the data processing functions described above can be complex. This has consequences on the effort required when developing the related computer code, affecting the development of the code and efforts to ensure its correctness. This has implications on the time requirements for software developments.

Using a DBMS makes it easier for the software developer to deal with data processing functions. It also results in a more transparent software structure and potentially more user-friendly software because it allows the developer to provide additional data processing options to the user. Key DBMS features that relate to the use in a simulation environment are described below.

4.4.1 Query functions

Database programs allow the definition of operations via query definitions. Query functions can be used to define in a structured way operations that change, view or analyse data. In doing so, queries also recognise and consider data relationships. Queries are at the heart of database programs and can efficiently handle simulation data within a database environment. The DBMS used to create the ODS-Interface [Microsoft 1999, Novalis 1999] provides with its graphical query definition tool several query types and also supports some Standard Query Language (SQL) queries. The former queries are summarised in Table 4.1.

Query	Description
Select	Retrieves stored data in the database.
Crosstab	Displays values and groups them by two sets of facts in vertical and horizontal direction.
Make-table	Creates a new table from all or part of the data in one or more tables.
Update	Modifies specific fields in existing records.
Append	Appends a new record to a table.
Delete	Deletes a record from a table.

Table 4.1: Different query types

When using query functions, vital processes of an early design stage simulation tool such as copying of a simulation model in order to create a new design version can be carried out in a structured manner. However, with queries it is also possible to extract data sets that can then be used to increase the functionality of dynamic building simulation. One example of this in the ODS-Interface is its option to highlight all surfaces that have a default construction attribution and the ones where the user has carried out local changes. In this case, one query ("DEOP_qrySelectSurfacesCon", see Figure 4.3) carries out several processes: (1) find in the database all the attributed surfaces of the particular Design Version, (2) compare the construction attributed to each surface with the construction just selected by the user and (3) extract the name of these surfaces. With this data, it is possible to give comprehensive visual feedback during construction attribution, using the graphical model representation – a function which was ranked as useful by Donn [1997].

4.4.2 Increased transparency in the data structure

The data structure of a simulation model is complex. The reasons for this are:

- A simulation model contains a large set of data, including geometry definition, zone function definition, control schemes and construction data.
- The data of a simulation model relates to different ‘‘levels’ of a building, ranging from the building itself (e.g. its location) to zone functions, surfaces and elements of multilayer constructions.
- Different users define the data: support databases will be populated by the system administrator, but the building geometry will be defined by the user of the program. In the process of creating a simulation model this user then attributes the geometry with data from the support databases.
- For each geometry the user often defines a number of design variants.

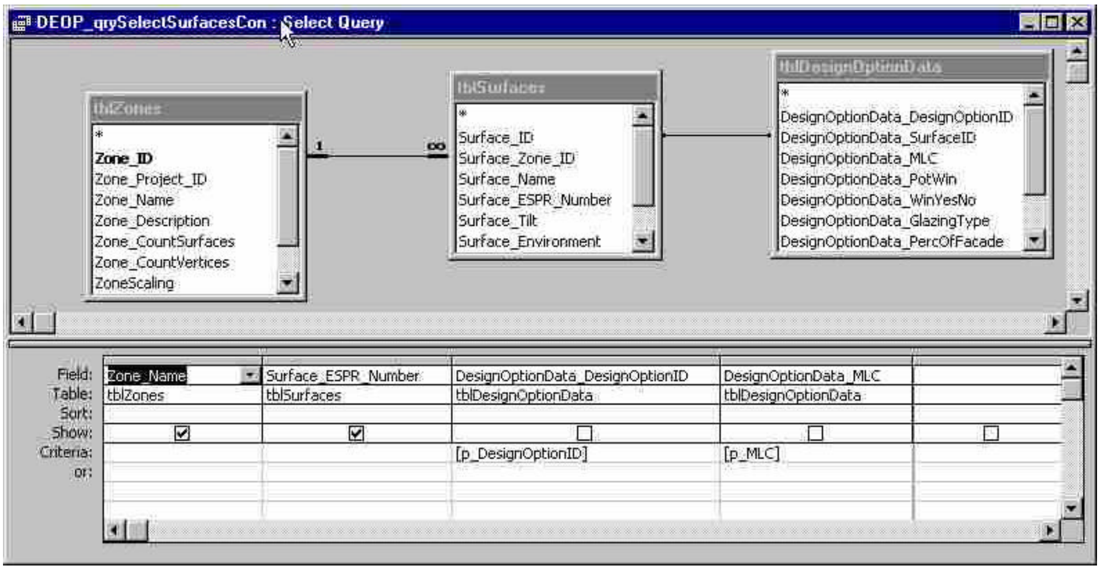


Figure 4.3: The DEOP_qrySelectSurfacesCon query

Attention to the relationship between data elements is important for software development and correct data processing. Past research work undertaken during the COMBINE project (Computer Models for the Building Industry in Europe) [Augenbroe 1994, Clarke et al 1995] had the aim of constructing an integrated data model and, in one case this resulted in the identification of inconsistent data relation definitions within ESP-r [Hand 1998]. Using DBMS supports such efforts.

4.5 The ODS data model

4.5.1 Review of data models

Data models (or product data models) are abstract representations of the information structure of a product, which are then converted into a digital format. The data model contains definitions of objects and the relationships between these objects. The definition of a data model can be applied to any industrial product, not only buildings. In the context of buildings often the term "building data model" is used. Research into data models in the built environment has been underway since the 1970s and has been under constant development ever since [Citherlet 2001].

Many of these data models were developed independently and often in parallel, which resulted in a lack of communication capabilities between the different software tools that use them and thus difficulties in sharing information between the different models. These limitations resulted in projects such as the COMBINE project, STEP (Standard for Exchange of Product Data) [ISO 1989] or the Industry Foundation Classes (IFC) [IAI 2002], developed by the International Alliance for Interoperability (IAI).

STEP can be seen as the largest general effort currently underway in the development of data models. It is run by the International Standard Organisation (ISO) and has the aim of developing standards for representing information about products in many different industries. The official name of the program is *ISO Standard 10303, Product Data Representation and Exchange*. Ultimately, the aim is to provide product design and production data in a format that can be exchanged between computer systems such as Computer-Aided-Design (CAD), Computer-Aided-Engineering (CAE) and Computer-Aided-Manufacturing (CAM). The building construction effort within STEP is called *Application Protocol Planning Project for Building and Construction* and covers work in different areas: Explicit Shape Representation, Structural Frame and Building Services.

IAI was established in 1995 by American and European architecture, engineering and construction (AEC) firms to promote interoperability in the industry. Currently the organisation has 650 member companies worldwide. Building software developments nowadays seem to focus more on compliance with the IFC rather than STEP [Bazjanac 1997, Bazjanac 2001]. Tangible deliverables so far in the IFC are mainly in the field of the building geometry definition [Augenbroe 2002].

The Combine Project was split into two phases: Combine I and Combine II. The first phase (1990-1992) developed new methods to enhance data sharing between different design applications in the fields of energy efficiency and building services engineering. The second phase (1993-1995) focused on the development of mechanisms that control the process flow and keep track of the interdependent data (managing the transactions between users and design tools).

4.5.2 General considerations for the development of data model

A number of aspects needed to be addressed and considered when defining the data model for the ODS-Interface: (1) the Universe of Discourse, (2) the appropriate decomposition of the data objects and (3) the definition of the relationships between components. They are discussed in the following section.

Universe of Discourse (UoD)

A data model represents information related to a certain part of the real or abstract world. This is the so-called Universe of Discourse (UoD). In the STEP and IFC programmes the UoD relates to the entire building. The aim of the data model defined in this project was not to provide a solution for the entire construction industry, but to focus on the application of building simulation at early building design stages.

Decomposition of the UoD into components

In the process of a data model definition the UoD is divided into different components. This process is called decomposition. The appropriate decomposition of a UoD will depend on the intended usage of the data model The following example illustrates how data models can change with changing requirements.

Figure 4.4 depicts three main classifications that the user distinguishes when creating a simulation model using the ODS-Interface: (1) Project, (2) Design Option and (3) Design Version where a Design Option is a certain geometry definition for a project and Design Versions are differently attributed Design Options. This structure is also reflected in the data model of the ODS-Interface. Therefore, the component “Design Option” contains data that relates to the geometry of the proposed building, and the component “Design Version” relates to this geometry with information about constructions used, zone functions, window areas, etc. This issue is also discussed later in section 4.5.3 under the section ‘Relationships’.

Relationships between components

Dividing the UoD into different entities is one of the tasks that has to be undertaken when creating a data model. Another task is the definition of the relationship between the different entities while maintaining model integrity, allowing the management and traceability of information flow and avoiding data redundancy.

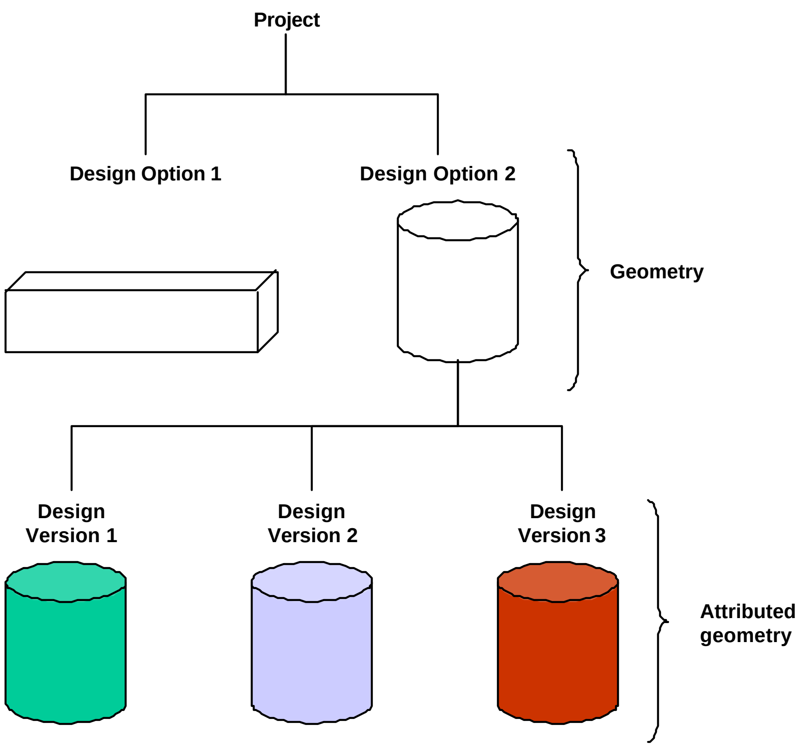


Figure 4.4: Project, Design Option, Design Version data structure

4.5.3 Entity-Relationship Models (ERM)

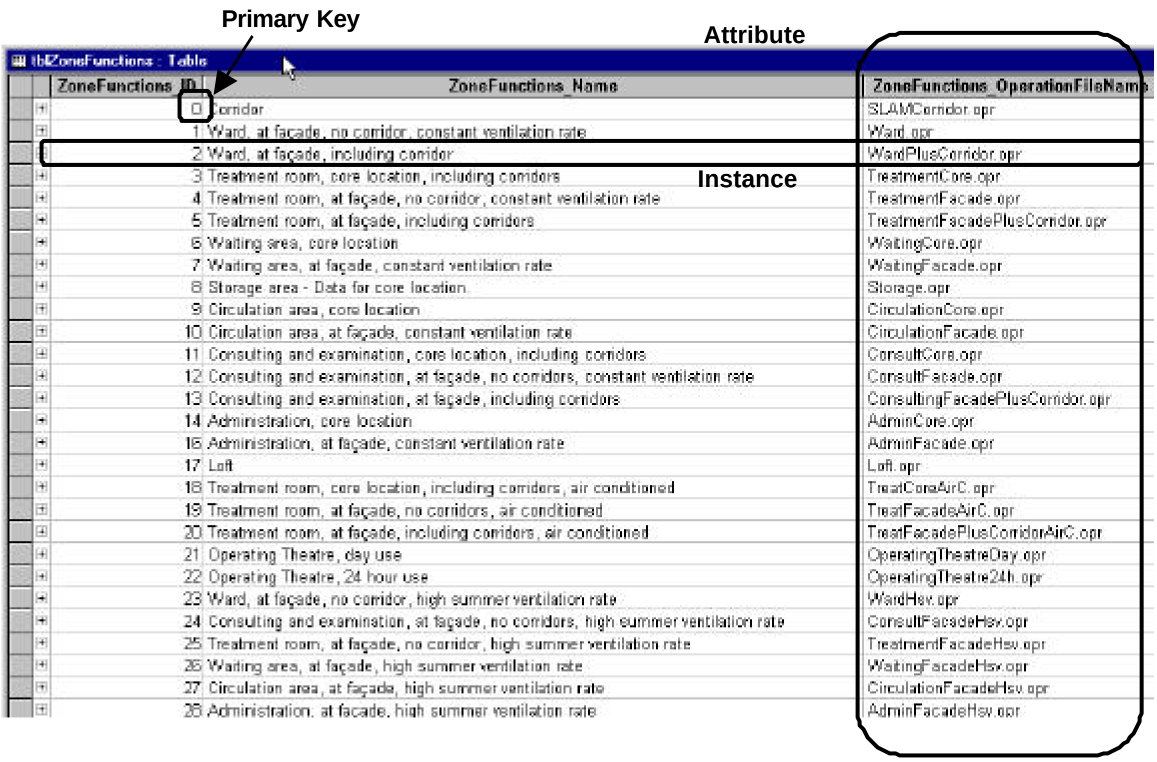
After introducing the concept of a data model this section describes a way to map these models onto actual applications via an Entity-Relationship Model (ERM). An ERM is represented by means of three primitive objects:

- Entities, which represent the components being modelled.
- Attributes, which represent the properties of the entities.
- Relationships, which represent the associations among entities.

An Entity-Relationship Model was used for the specification of the ODS-data model.

Entity, attributes and instances

An entity[1] stores descriptive information about a particular component such as a Design Option, surface or the zone function support database. An entity itself is defined by its attributes[2]. An attribute of the entity "zone" would be data about the zone name or the related Design Option. An entity type has normally a number of instances[3]. An instance would then be one zone of a particular Design Option. To be able to uniquely identify each instance it is necessary to define one or several primary key(s) (also named ID) from among the different attributes. A primary key of a Design Option could be the related Project Number or the primary key of a zone could be the related Design Option number. Figure 4.5 gives examples for primary keys, attributes and instances.



ZoneFunctions_ID	ZoneFunctions_Name	ZoneFunctions_OperationFileName
0	Corridor	SLAMCorridor.opr
1	Ward, at façade, no corridor, constant ventilation rate	Ward.opr
2	Ward, at façade, including corridor	WardPlusCorridor.opr
3	Treatment room, core location, including corridors	TreatmentCore.opr
4	Treatment room, at façade, no corridor, constant ventilation rate	TreatmentFacade.opr
5	Treatment room, at façade, including corridors	TreatmentFacadePlusCorridor.opr
6	Waiting area, core location	WaitingCore.opr
7	Waiting area, at façade, constant ventilation rate	WaitingFacade.opr
8	Storage area - Data for core location	Storage.opr
9	Circulation area, core location	CirculationCore.opr
10	Circulation area, at façade, constant ventilation rate	CirculationFacade.opr
11	Consulting and examination, core location, including corridors	ConsultCore.opr
12	Consulting and examination, at façade, no corridors, constant ventilation rate	ConsultFacade.opr
13	Consulting and examination, at façade, including corridors	ConsultingFacadePlusCorridor.opr
14	Administration, core location	AdminCore.opr
16	Administration, at façade, constant ventilation rate	AdminFacade.opr
17	Loft	Loft.opr
18	Treatment room, core location, including corridors, air conditioned	TreatCoreAirC.opr
19	Treatment room, at façade, no corridors, air conditioned	TreatFacadeAirC.opr
20	Treatment room, at façade, including corridors, air conditioned	TreatFacadePlusCorridorAirC.opr
21	Operating Theatre, day use	OperatingTheatreDay.opr
22	Operating Theatre, 24 hour use	OperatingTheatre24h.opr
23	Ward, at façade, no corridor, high summer ventilation rate	WardHsv.opr
24	Consulting and examination, at façade, no corridors, high summer ventilation rate	ConsultFacadeHsv.opr
25	Treatment room, at façade, no corridor, high summer ventilation rate	TreatmentFacadeHsv.opr
26	Waiting area, at façade, high summer ventilation rate	WaitingFacadeHsv.opr
27	Circulation area, at façade, high summer ventilation rate	CirculationFacadeHsv.opr
28	Administration, at facade, high summer ventilation rate	AdminFacadeHsv.opr

Figure 4.5: Examples of primary key, attributes and instances of an entity (here: Zone Functions)

A relationship is a named association between two or more entity types. Three different relationships are commonly used in DBMS:

[1] In some DBMS user manuals the word "table" is used instead of "entity".

[2] In some DBMS user manuals the word "field" is used instead of "attribute".

[3] In some DBMS user manuals the word "record" is used instead of "instance".

- one-to-one-relationships,
- one-to-many-relationships,
- many-to-many relationships.

The data model of the ODS-Interface uses mainly one-to-many-relationships but in some cases also one-to-one relationships. Figure 4.6 explains the concept of a one-to-many relationship: each surface is always related to one zone, but each zone can be related to a number of surfaces. Figure 4.7 shows that a relationship can be more complex: the zone function data is related to a zone but also (indirectly via the support database) to a building type. This ensures that during the attribution process for the zone function data only items are selected that relate to the building type of the Design Option (e.g. if a Design Option has been specified as a office building the user cannot specify a zone to be a ward).

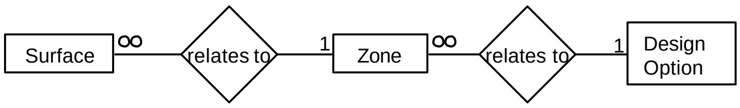


Figure 4.6: The relationship between Design Option, zone and surface

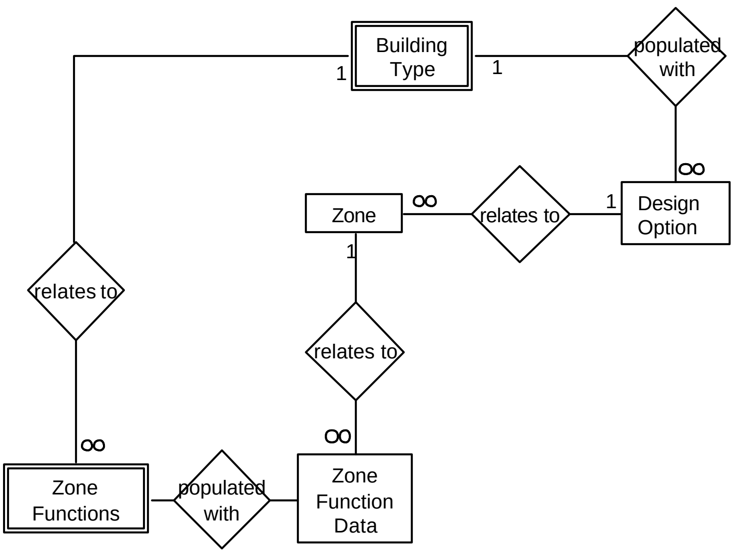


Figure 4.7: The relationship between Design Option, Building Type, Zone Function, Zone Function Data and Zone

4.5.4 The ODS-Interface data model

After introducing data models and Entity-Relationship Modelling this section introduces the ODS-Interface data model. The data model comprises three different databases: (1) Design Option Database, (2) Design Version Database and (3) Support Database. The three databases are not separated but linked and integrated in one data model. An overview of the ODS-Interface data model is displayed in Figure 4.8. A full description of the data model can be found in Appendix 1. The following description covers only the information types held in the different databases.

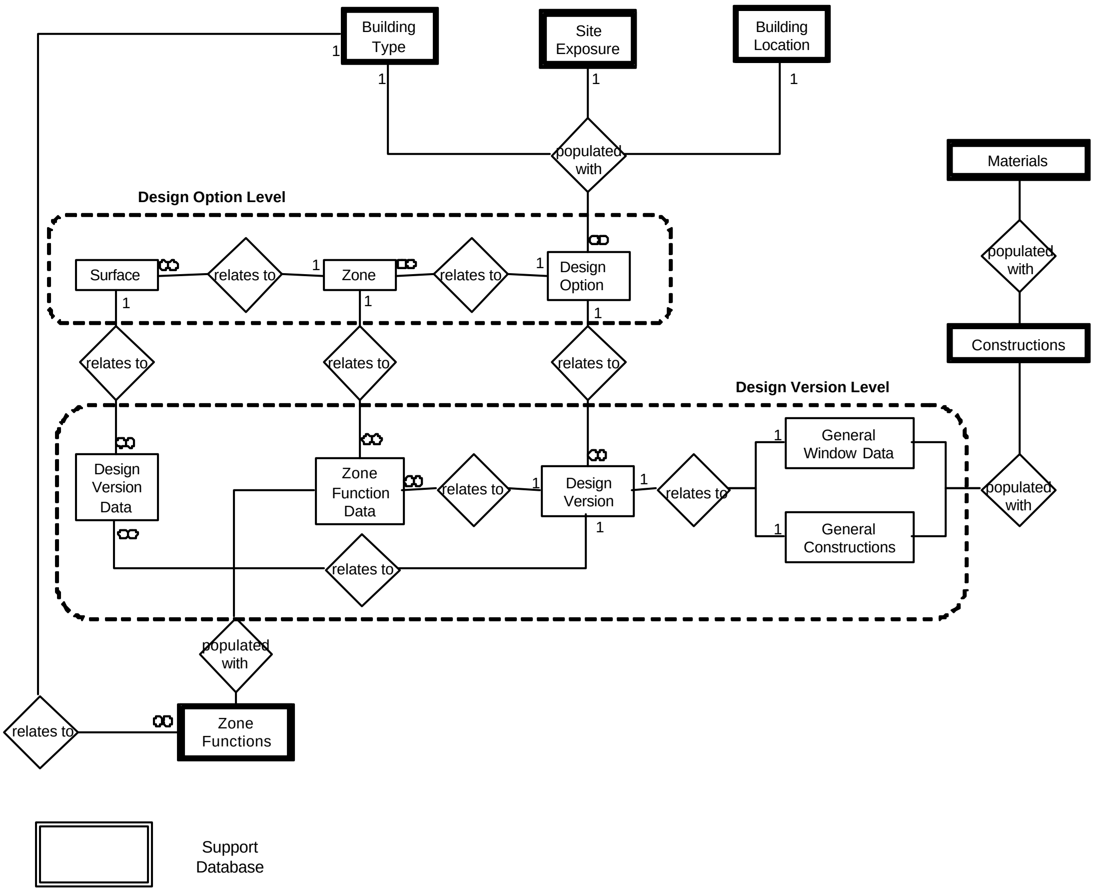


Figure 4.8: The ODS-Interface data model with different entities of the data model and their relationships

Design Option Data

The Design Option Database contains information about the Project the Design Option refers to and geometry data of the Design Option. Project information includes the building type, the building location and the site exposure. Geometry data includes information about the zones (e.g. ID, name, scaling factor) and surfaces (e.g. ID, related zone ID, surface name, environment on the other side, surface tilt).

The data for the different Design Options is either directly defined by the user (e.g. site exposure, scaling factor), or generated by the program based on CAD geometry definition imported by the user (this data import is discussed in section 4.6.3). It is not possible to change the data of a Design Option once it has been created. This ensures data consistency between a Design Option and the Design Versions that were built based on this Design Option.

Design Version Database

The Design Version Database contains data attributes of the building geometry. This includes data about the construction type for each surface, the glazing area and glazing type of each surface with a window and zone function definition for the different zones. The data of the Design Version is defined by the user. It is again not possible to change single data items of one Design Version, but it is possible to copy and alter a Design Version. Hence, by being able to refer to previous Design Versions the model creation process is closer to an approach where the user is able to 'undo' changes, which was indicated as useful but often not implemented into contemporary building simulation programs [Hand 1998].

Support Databases

In the process of Design Option and Design Version definition the user applies Support Databases. These databases are available at both the Design Option Level (e.g. building location, building type) and Design Version Level (e.g. zone function, constructions). The Support Databases are populated by the system administrator who has experience in simulation and can ensure appropriate data definition.

4.5.5 Comparison of the ODS-Interface data model with other data models

Section 4.5.1 introduced data models developed in the built environment. This section compares the data model developed with three other data models:

- the data model of the full ESP-r program [Clarke et al 1995],
- a data model for multiple view assessment [Citherlet 2001],
- the Building Design Advisor (BDA) data model [Papamichael 1999, Papamichael et al 1999].

The ESP-r data model

Because of the wide variety of user functionality and the detail in the simulation model definition it can be concluded that the ESP-r data model is one of the most comprehensive data models that relate to the simulation environment. During the COMBINE project, research was undertaken with the aim of decomposing parts of the ESP-r data model (building side, network flow and control data). This formal decomposition was then used to define the protocols for data exchange between the different objects.

A data model for multiple view assessment

In his research Citherlet [2001] developed a data model for a conceptual building model to support a multiple view representation over the whole building life cycle. For this purpose issues such as the geometrical and construction attributes decoupling, life cycle based decomposition and the representation of a building element for different views at various levels of detail were introduced. With this research Citherlet extended the ESP-r simulation data model to a more holistic UoD by including data of the whole lifespan of the building.

The Building Design Advisor (BDA) data model

The BDA data model is currently under development. The ultimate aim of this work is the inclusion of thermal, lighting and air flow simulation and the inclusion of cost estimating and environmental impact modules, building rating systems, CAD software and an electronic product catalogue. With these features incorporated, the data model of the BDA can expected to be a comprehensive representation of building simulation data. However, the BDA is still under development and currently contains only a fraction of this data.

Like the ODS-Interface, the BDA uses a database program for data operation [Papamichael 1999, Papamichael et al 1999]. It also uses the concept of support databases for the model creation process (e.g. zone functions). In contrast to the ODS-Interface, it makes all the data underlying a certain data definition accessible to the user and allows editing of this data. This is an option that was found inappropriate for the ODS-Interface, because the user will not be a simulation expert.

4.6 CAD link

The previous section described the data model in the ODS-Interface. This section deals with an important aspect of data definition in a simulation environment – the geometry definition of the simulation model.

4.6.1 Introduction und justification

Both dynamic thermal and lighting simulation require the geometry definition of the building or the building section to be simulated. For such purposes different simulation tool developers have developed so called “native file formats” which need to be followed when defining the geometry of a simulation model.

In the early days of simulation the user had to specify the geometry in an ASCII file following the native file format with no visual feedback. This made the geometry definition process difficult and could easily result in input errors, either because of wrong data definition or incorrect file formats. To ease the geometry definition the developers of building simulation programs integrated enhanced geometry definition functions into their software tools.

Despite the fact that the in-built functionality of some building simulation programs allows quick geometry definition and also provides visual feedback as part of the processs they still are not as flexible as state-of-the-art CAD tools. As a consequence, efforts have been made in the past to deploy CAD tools for the geometry definition of a simulation model.

As part of the COMBINE project filters for example, were developed that could transfer an IGES and DXF file into a format recognisable by the ESP-r simulation software. However, neither CAD file format automatically recognises surfaces and volumes. Thus, in order to use a CAD tool such as AutoCAD, the user had to follow certain conventions to ensure that the data is saved in a format from which the simulation program can derive the surface and zone information it needs.

With a wider awareness of these limitations and restrictions, a number of projects were undertaken that addressed this issue (see section 4.5.1). One of these is the Industry Foundation Class (IFC), which has defined a general data model for the geometry definition of a building. A number of CAD tools are now able to save a drawing in this format (AutoDesk, Visio), and some dynamic building simulation programs are now able to import this data format [Bazjanac 2001].

Using CAD tools for the definition of a simulation model geometry has the advantage that the designer can utilise the advanced user functions that these tools provide. It is also possible to save each zone in different layers, which allows their display in different colours. It is also possible for each zone to choose different phase status (editable, hittable, visible and invisible, see Figure 4.9). This, together with functions such as snapping to distinct points of the drawing (vertex, line, middle of line) provides an environment that enables the quick and efficient definition, modification and good visualisation of simulation models.

Using a CAD tool also has the advantage that it allows different model displays: It can be depicted in wire fame, hidden line or rendered view. Figure 4.10 shows the same model in these three different views. It can be seen that offering alternatives to the wire frame views that are often found in simulation programs can make it easier to comprehend the simulation model geometry. This helps the designer carrying out the simulation exercise but is also beneficial if people who have not been involved in the simulation exercise want to view the model. Examples are designers who use simulation results or clients who view the simulation tool.

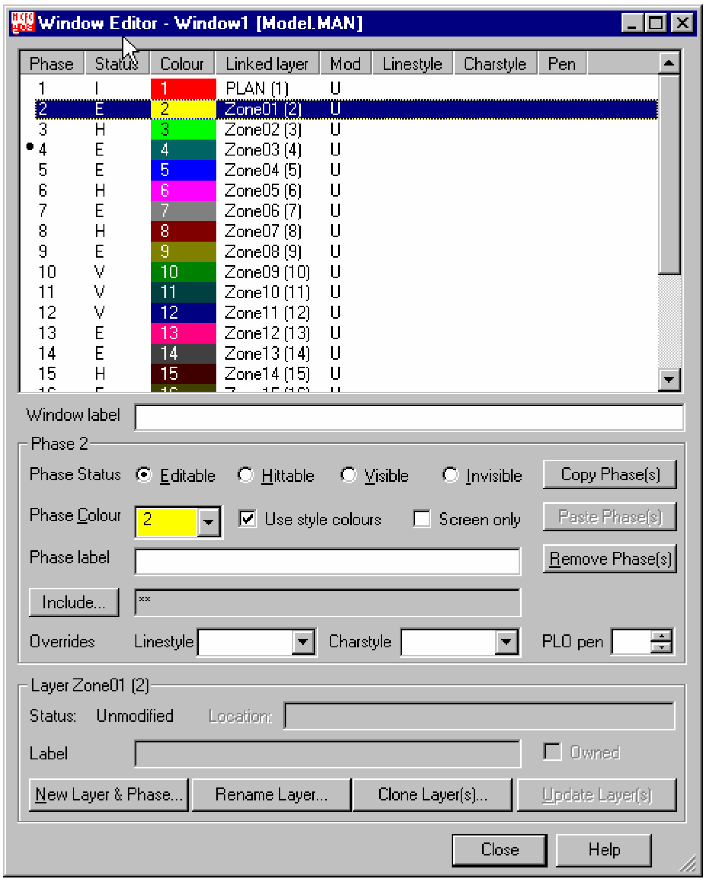


Figure 4.9: Specification of layer colours and phase status

4.6.2 MicroGDS

The CAD software utilised in this project for the specification of a model geometry [Cambridge Data Systems 1999] is not IFC compliant. This section describes why it was nevertheless seen as the most appropriate CAD tool to apply in this research project.

Applied in architecture company

MicroGDS is the only CAD tool that is used in the architecture company that provided the test bed for the research project. It was stated earlier (section 4.2.5) that building simulation should be integrated into early building design stages by linking it as much as possible to established design support tools and structures. This was seen as relevant for the geometry definition of the simulation model in particular.

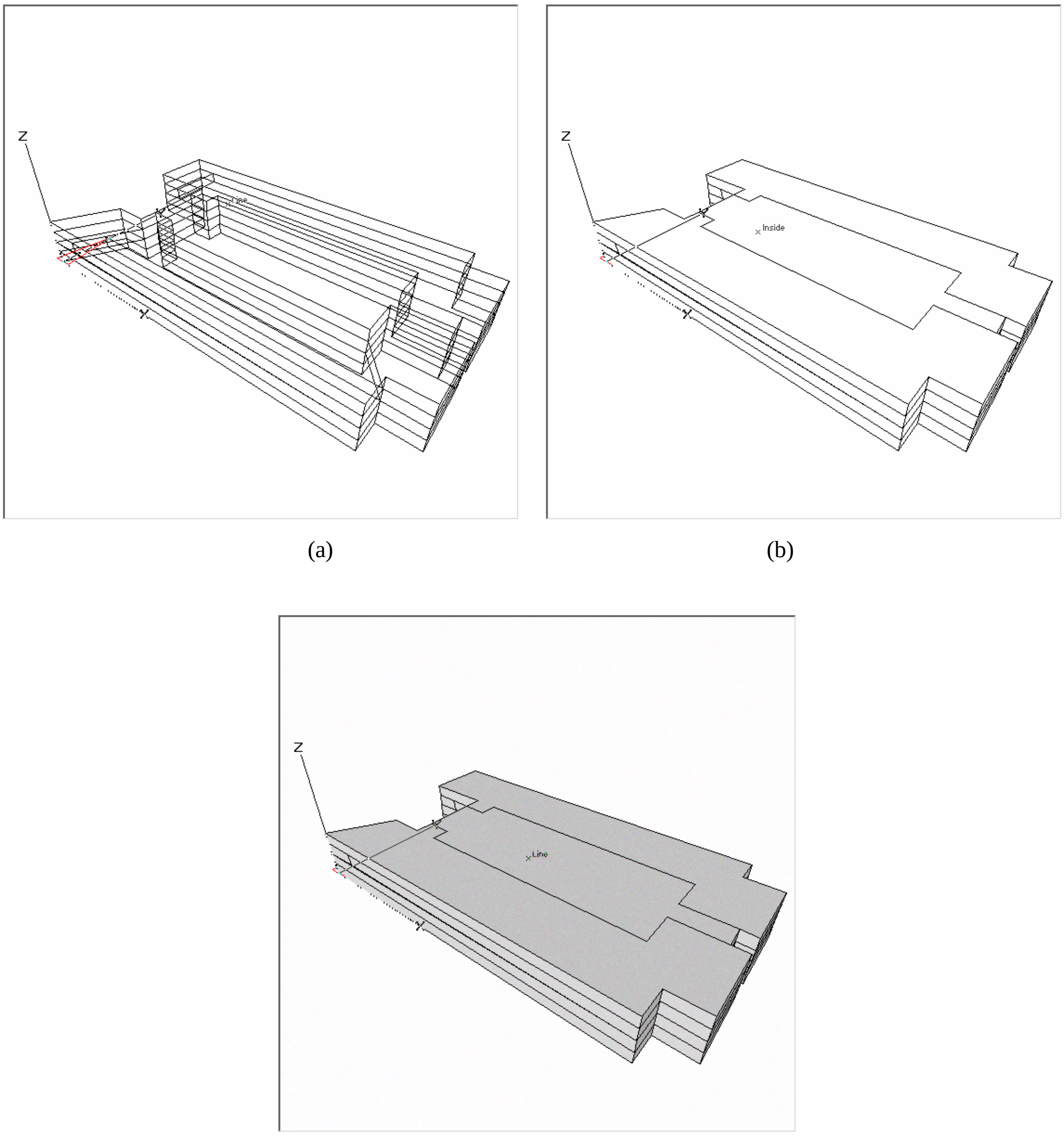


Figure 4.10: Different display types: (a) wireframe, (b) hidden line (c) and rendered view

Zone and surface definition

MicroGDS is able to define volumes (zones) and areas (surfaces). Both are an elementary component of any simulation geometry definition. In the MicroGDS naming convention the ESP-r object “zone” is called a “clump” and a “surface” is called a “face”. In the following, the ESP-r naming convention will be used.

Related file format

MicroGDS allows the user to save a drawing in 3D ‘things’ file format; ESP-r holds geometry data of a simulation model in geometry files (*.geo), with a geometry file being specified for each zone. The data definition conventions are identical in both files; differences are found only in the file layout. Both files first list the vertices and then use the defined vertices to specify the surfaces of the zone. In addition the ESP-r file requires information related to the name of the surface, surface inclination, a construction attribution and a definition of the environmental conditions on the other side of the surface. At the time of importing the model geometry into the ODS-Interface, of the additional attribution requirements only the surface name is known. However, in ESP-r, all the other attributes can initially be defined as “UNKNOWN”. This causes no problems in running is ESP-r.

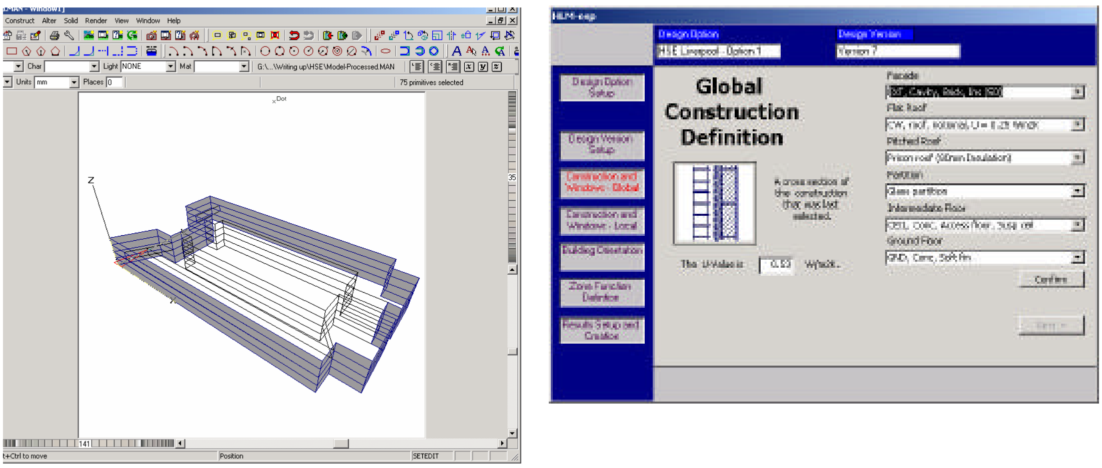


Figure 4.11: Relevant surfaces (here all façade surfaces) are highlighted in the CAD drawing

Use of CAD-software for geometry selection indication

During the creation of a simulation model it is necessary to be able to indicate zones or surfaces to the user. Examples of this are the attribution of zones with zone functions and surfaces with constructions, but also the check of correct surface connections during the geometry import by providing visual feedback to the user. With the ODS-Interface this is done in the CAD-drawing previously created by the user. Figure 4.11 shows how the ODS-Interface highlights all the surfaces that relate to the general construction of the type ‘façade’.

4.6.3 Data import

General procedure

The import of the model geometry data defined with the CAD tool happens in a seven-step process: (1) save drawing as 'things' file, (2) create ESP-r geometry file based on 'things' file, (3) create simulation model folder structure, (4) copy geometry files and import data into database, (5) create connection and geometry files which are required to run a simulation, (6) detect surface tilt and environment on other side and (7) import data into database. Figure 4.12 depicts the process. Note that the entire process is automated.

If the user needs to change the geometry, the geometry needs to be re-imported as a new Design Option. This 'geometry freeze' is a general limitation when building simulation tools use CAD software to define the geometry of a simulation model and has been addressed in theory by Suter et al [1999] and Suter and Mahdavi [1998]. Only complex coding can ensure that after a geometry change such as, for example, the splitting of surfaces in a zone, the program will still create a correct attribution of the new geometry with data from a model that was attributed on the basis of the initial geometry. The above example would bear the risk that the change in surface numbers and potentially also the order in which they are imported will result in an incorrect construction attribution.

QA-issues during geometry import

The correct representation of the simulation model geometry requires that for each zone the accurate size, dimensions and location in space are given. In addition, it is also important that the surfaces of each zone allow the detection of adjacencies to other zones. The ODS-Interface will automatically determine adjacencies by invoking a vertex continuity check performed by ESP-r. A QA check provides a visual representation of these different surface types during the data import and allows the user to ensure correct geometry definition. This issue is discussed in more detail in section 6.3.3.

4.7 Guided input procedure

Figure 4.13 shows that with the ODS-Interface a model is created in a sequence of steps. This is vital for the guided input procedure, which was identified at the outset as important for the integration of simulation at early building design stages. Additional features of the ODS-Interface further eased the model creation process.

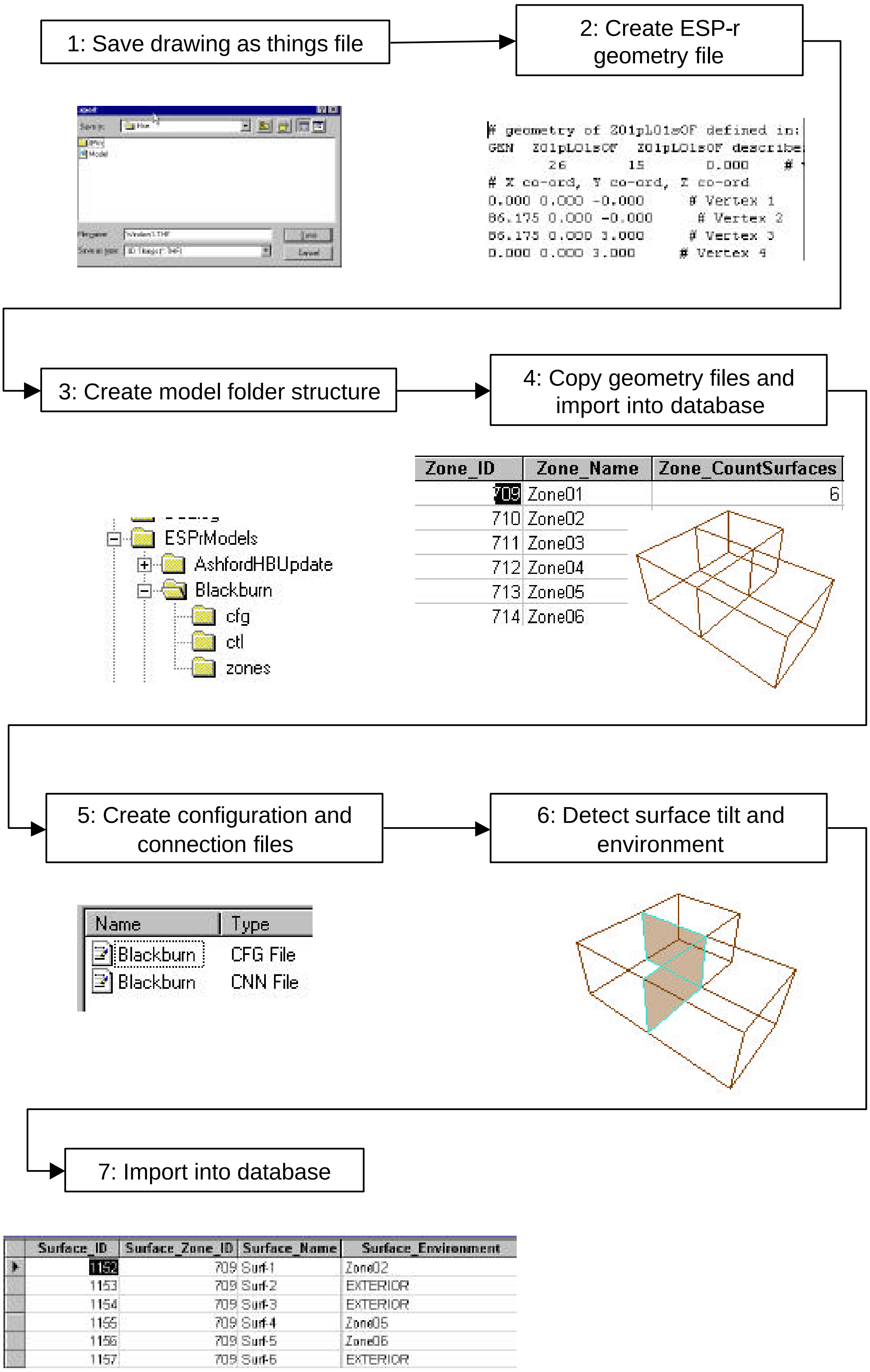


Figure 4.12 Diagrammatic display of the geometry import into ODS-Interface

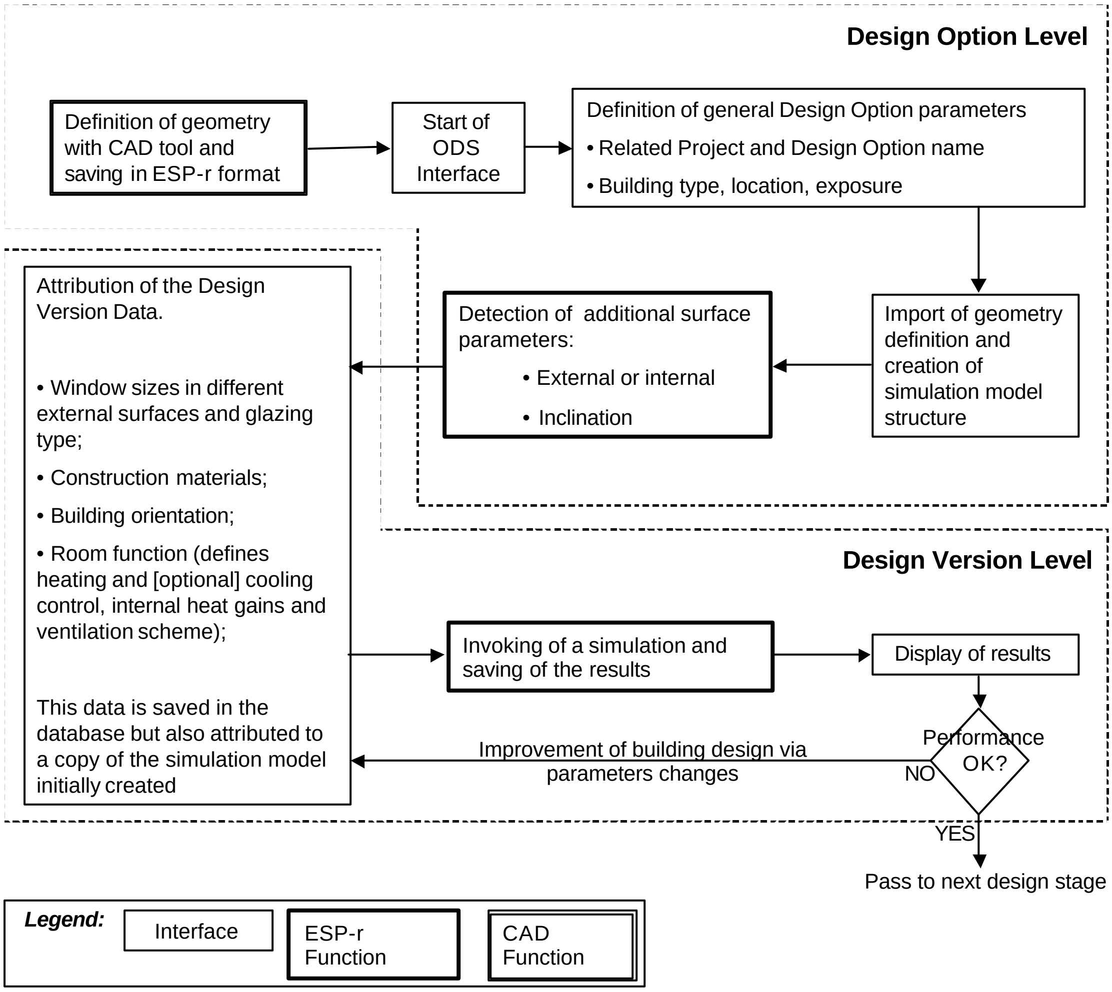


Figure 4.13: The ODS-Interface program structure

When creating a model the user moves through a number of interface windows (see Figure 4.14 for an example and Appendix 2 for the entire attribution process). In every window the user specifies certain model data (general construction data, local construction and window data, zone types, etc.). After having completed the current task the user moves via the "Next" button to the next window (and hence task). The program checks that all the data that relates to the current task has been defined and is consistent. If this is not the case it is pointed out to the user and it is not possible to move to the next task. This gives the user confidence when using the program and also ensures that only complete models are created.

All the tasks that are required to create a simulation model are displayed as icons in the Navigation Window. The current task is highlighted. Icons above relate to tasks that have been completed, icons below indicate what still needs to be done.

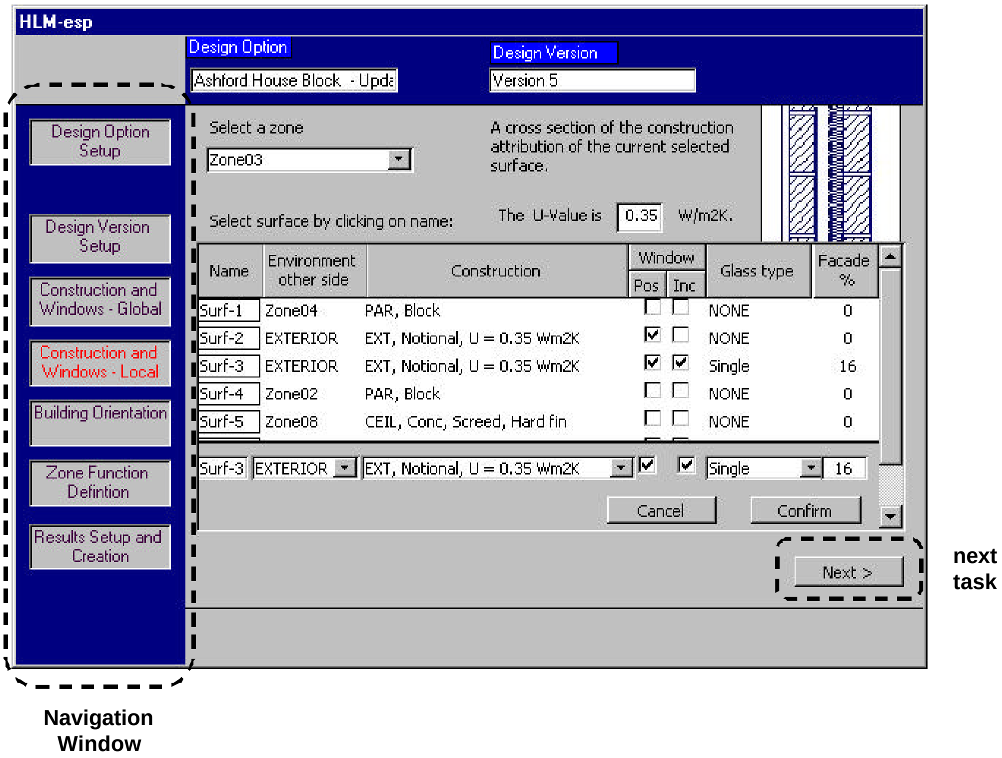


Figure 4.14: Example of the ODS-Interface

The guidance provided is not only limited to the input procedure. The program also clearly distinguishes between the Design Option and Design Version Level. When starting the program the user is provided with a list of the different Design Options that were previously created. From here it is possible to delete a Design Option, view its Design Versions or create a new Design Option. When viewing a Design Option the user is provided with a list of all the Design Versions, which can again be deleted or copied, or a new Version can be created.

4.8 Support Databases

The Support Databases are another important element of the ODS-Interface. Table 4.2 lists the different Support Database entities. They have been populated with data from recognised data sources [CIBSE 1998, CIBSE 1986] or past projects of the architecture company.

At the Design Option level, the Support Databases are used to attribute data that relates to the building type and location. At the Design Version level, the Support Databases are used for the attribution of construction materials to the different surfaces and function types to the different zones. Constructions are attributed in two subsequent steps: an initial global definition of all the surfaces followed by (optional) local definitions. The zone function definition is used for the attribution of several zone related model parameters: the heating and cooling control scheme of the zone, its ventilation rate and internal gains. They are defined in a two-step process: first the user defines the zone function (e.g. ward, operating theatre, waiting area) and then additional, more detailed information (e.g. core or façade location, occupancy time) that specifies the zone function type. With this approach it was ensured that the data definition requires little time but still provides a level of accuracy normally found in advanced building simulation program models. Figure 4.15 shows an image of the interface where the user defines the zone function and zone function type.

Type	Underlying data	Level
Building type	Control file name, zone function list	Design Option
Building location	Climate set; latitude and longitude; typical seasonal days.	Design Option
Façade construction	Construction layer definitions; optical properties (optional).	Design Version
Flat roof construction	Construction layer definitions; optical properties (optional).	Design Version
Sloped roof construction	Construction layer definitions; optical properties (optional).	Design Version
Partitions	Construction layer definitions; optical properties (optional).	Design Version
Intermediate floor constructions	Construction layer definitions; optical properties (optional).	Design Version
Ground floor construction	Construction layer definitions;	Design Version
Zone function	Zone function types;	Design Version
Zone function type	Heating and cooling control scheme; ventilation rate; internal gains; zone function description	Design Version

Table 4.2: The different support databases

Apart from changes to the zone function or zone function type the user has no possibility to edit the operational or control data of a zone. This is an important difference from Building Design Advisor, which also operates with support databases but then gives the user full access to the data that has been imported from the Support Databases. Support Databases significantly reduce the time required to create a simulation model because a large amount of data is attributed in automated background processes. This reinforces in connection with the time constraints of the Outline Design Stage the importance of the Support Databases for the ODS-Interface.

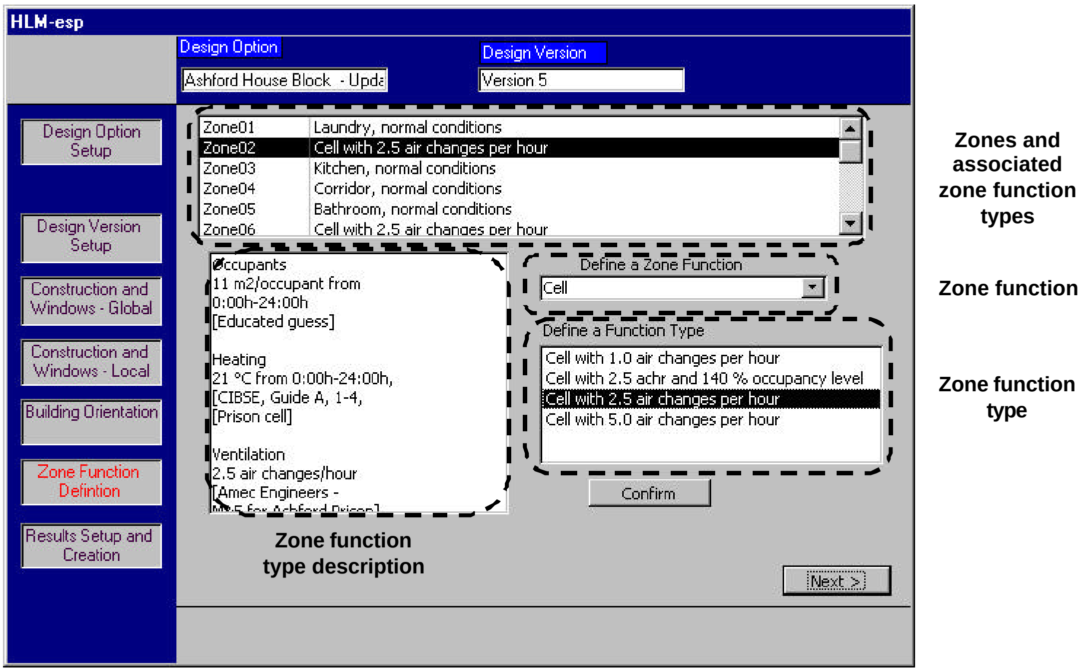


Figure 4.15: The definition of the zone function and its type

4.9 QA facilities provided by the ODS-Interface

In addition to quicker model definition, the Support Databases also support QA during the model creation process. Firstly, by reducing input error risks due to the fact that a large amount of data is specified by the ODS-Interface and not by the user. Secondly, because the typical user of the ODS-Interface is not a simulation expert and has therefore only limited knowledge of suitable operational or control data definition, which can lead to incorrect data definitions. With the data sets obtained from the Support Databases (which again have been populated with information from established data sources) it is ensured that the model is attributed with appropriate data.

Another important QA feature of the ODS-Interface is the extensive visual feedback in the CAD-drawing by highlighting surfaces and zones. Visual feedback is for example given during the import of a MicroGDS geometry definition, when the ODS-Interface highlights surfaces it has detected as external and internal. Hence inconsistencies of internal T-intersections (which might be detected as external) are pointed out to the user. Surfaces are also highlighted during the general construction and window definition as well as during the local surface specification. Zones are highlighted during the zone function definition.

4.10 Comparison with other software packages

Having described the structure of the ODS-Interface, this section compares the program to four other simulation tools: the ESP-r system, the Building Design Advisor (BDA), the LT-Method and Energy 10.

4.10.1 Full ESP-r system

The ESP-r system allows advanced, detailed simulation exercises. However, as previously stated the complexity of the program and the amount of detailed information required to create a model make the program unsuitable for early building design stages and for non-simulation expert users.

4.10.2 BDA

The BDA has functionalities that are also found in the ODS-Interface, especially the support databases. However, the data defined is fully accessible to the user (view and edit), this was deliberately not incorporated into the ODS-Interface. The program also offers a large number of possible design variations without providing structured guidance on how to specify these in the simulation model. From the research undertaken, both can be seen as problematic aspects when employing the program at an early building design stage by non-simulation experts.

4.10.3 LT-Method

The LT-Method allows a very quick building design evaluation. Architects have sufficient background knowledge to define a simulation model. This makes the program suitable for use in the early building design stages. The detail in model definition and performance predictions that the LT-Method can carry out on the other hand is limited (see section 2.4).

4.10.4 Energy 10

Energy 10 has several elements that are either required or very useful for the employment of simulation at early design stages:

- Energy 10 uses a guided input procedure when creating a simulation model.
- The program addresses different levels of model detail at different building design stages.

- It attempts to show the user of the program not only how the building performs but also to highlight how the different design elements influence the building performance.

A drawback of Energy 10 is its very simplified simulation model definition. For the Outline Design Stage the model comprises a maximum of two zones and operational attributes are only based on the definition of the building type. This can lead to simulation results that are significantly different from the actual performance of the building.

4.11 Closing remarks

This chapter introduced the ODS-Interface, which was developed with the aim of enabling non-simulation experts to create detailed simulation models at early building design stages.

The program is based on a DBMS. The chapter highlights that the application of dynamic building simulation involves the frequent processing of data and that DBMS with their query functions and explicitly defined data structures support such requirements.

In the ODS-Interface, there is a clear separation of Design Options and Design Versions to ensure data integrity and to avoid data redundancy along with the integration of support databases.

Apart from DBMS software, the ODS-Interface also utilises a CAD program. It was also indicated that apart from the utilisation of advanced CAD user functions and different visual display types, the link also had the benefit of utilising CAD drawing to indicate surfaces and zones to the user. This, together with the option to use existing CAD drawings to create a simulation model, can be seen as an important first step to integrate simulation to the normal design work of the architects.

The chapter also discussed the concept of a guided input procedure, which was found vital to enable non-simulation experts who do not use the tool on a daily basis to create a correct simulation model quickly. In the process of creating a simulation model program users are provided with support databases to attribute the model.

Having introduced in this chapter the ODS-Interface the next chapter deals with the analysis of performance predictions.

References

Augenbroe G L M, "An Overview of the COMBINE Project", 1st European Conference on Product and Process Modelling in the Building Industry (ECPPM 1994), Dresden, Germany, 1994.

Augenbroe G L M, Personal Communication, 2002.

Bazjanac V, "Acquisition of Building Geometry and the Simulation of Energy Performance", Proceedings Building Simulation 01, Rio de Janeiro, pp 395-312, 2001.

Bazjanac V, "The Implementation of Industry Foundation Classes in Simulation Tools for the Building Industry", Proceedings Building Simulation 97, Prague, pp 203-210, 1997.

Cafferty D, Board Director of HLM Design, Personal Communication, 2000.

Cambridge Data Systems, "Using MicroGDS Advanced", MicroGDS User Manual for Version 6.0, 1999.

CIBSE (Chartered Institution of Building Services Engineers) "Commercial Management – Estimating Capital & Whole Life Costs", CPD Seminar Notes, 2000.

CIBSE (Chartered Institution of Building Services Engineers), "CIBSE Guide A - Environmental Design", CIBSE, 1998.

CIBSE (Chartered Institution of Building Services Engineers), "CIBSE Guide Sections B2/B3 – Ventilation and Air Conditioning", CIBSE, 1986.

Citherlet S, "Towards the Holistic Assessment of Building Performance Based on an Integrated Model Approach", PhD Thesis Swiss Federal Institute of Technology, 2001.

Clarke J A, Hand J W, Mac Randal D F, Strachan P, "Final Report for the COMBINE II Project, - Appendix 4 and 5: The ESP-r Model", University of Strathclyde, Glasgow, 1995.

Cooper G, Rezqui Y, Jackson M, Lawson B, Peng G, Cerulli C, "A CAD-based Decision Support System for the Design Stage of a Construction Project", Proceedings of the 5th International Conference on Design and Decision Support Systems in Architecture and Urban Design Planning, Eindhoven, pp 91-100, 2000.

Donn M R, "A Survey of Users of Thermal Simulation Programs", pp 65-72, Proceedings Building Simulation 97, Prague, pp 65-72, 1997.

Hand J, "Removing Barriers to the Use of Simulation in the Building Design Professions", PhD Thesis University of Strathclyde, 1998.

Hien W N, Poh L K, Feriadi H, "The Use of Performance-based Simulation Tools for Building Design and Evaluation – a Singapore Perspective", Building and Environment, Volume 35, pp 709-736, 2000.

IAI (International Alliance for Interoperability), "IAI Homepage", http://www.iai-na.org/, 2002.

ISO (International Organization for Standardisation), "ISO 10303: External Representation of Product Definition Data (STEP)", 1989.

LBNL (Lawrence Berkeley National Laboratory), "Building Design Advisor Homepage", http://kmp.lbl.gov/BDA, 2002.

Microsoft, "Discovering Microsoft Office 2000", Microsoft publication, 1999.

Novalis S, "Access 2000 VBA Handbook", SYBEX, 1999.

NREL (National Renewable Energy Laboratory), "Energy 10 Homepage", http://www.nrel.gov/buildings/energy10, 2002.

Papamichael K, "Application of Information Technologies in Building Design Decision", Building Research and Information, Vol. 27, pp 20-34, 1999.

Papamichael K, Chauvet H, LaPorta J, Dandridge R, " Product Modelling for Computer-aided Design Decision-making", Automation in Construction 8, pp. 339-350, 1999.

Pohl J, Chapman A, Pohl K J "Computer-aided Design in the 21st Century: Some Design Guidelines", Proceedings of the 5th International Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, pp 307-324, 2000.

Robinson D, "Energy Model Usage in Building Design: a Qualitative Assessment", Building Services Engineering Research and Technology, Vol. 17, No. 2, CIBSE, pp 89-95, 1996.

Suter G, Mahdavi A, "Generation and Communication of Design Information: a Building Performance Simulation Perspective", Proceedings of the 4th Design and Decision Support Systems in Architecture and Urban Planning Conference. Maastricht, The Netherlands, 1998.

Suter G, Mahdavi A, Kirshnamurti R, "A Performance-inspired Building Representation for Computational Design", Proceedings of the Eighth International Conference on Computer Aided Architectural Design Futures, Atlanta, pp 117-132, 1999.

Webster J, Regional Director of HLM Design, Personal Communication, 2000.

CHAPTER 5

PERFORMANCE PREDICTION ANALYSIS

5.1 Introduction

Software tools that allow the creation of simulation models in accordance with the requirements of the different design stages are important to encourage the integration of dynamic simulation into the building design process. The ODS-Interface described in the previous chapter was developed to enable this task at the Outline Design Stage. Once this has been successfully achieved, a designer can carry out simulation exercises that will provide performance predictions for a proposed building design. However, in addition it is also important to provide facilities that allow the analysis of this performance, otherwise simulation is not used to its full potential. This chapter describes research that was carried out in this area.

A variety of significantly different approaches can be taken when aiming to use simulation performance predictions to analyse and potentially improve the performance of a building. Depending on the approach the designer applies the input simulation will make into the design process will differ. It was therefore seen as important to review and discuss these approaches. This is covered in the first part of this chapter. It first speaks about the two main methods applied when using simulation to improve the performance of a building: the *causal analysis* and the *design guidance analysis* methods. It then reviews the *design assistant* and *design automation philosophy* behind DDSS. This is followed by a discussion of typical performance analysis at the different design stages.

The second part of the chapter introduces tools and techniques that were developed to support the actual analysis of performance predictions obtained from a simulation exercise. The research was influenced by findings described in the first part of the chapter. It first shows how the concept of the *Integrated Performance View (IPV)* has been taken on board and expanded for the purposes of a performance analysis *at the Outline Design Stage*. Then *data mining* is introduced as a novel way of analysing building performance predictions *at the detailed design stage*. It is also discussed to what extent the tool is applicable for this analysis and whether or not it is suitable for application in the building design process.

It is also important to point out that the expanded IPV and data mining are applied for different purposes. The former has the aim to enable non-simulation experts to obtain a general understanding what performance simulation has predicted for a certain building design (e.g. annual energy consumptions and comfort conditions that can be expected from the building, main reasons behind the building performance). Data mining has the aim to enable simulation and/or building services experts to obtain a detailed and in-depth understanding for the characteristics of a building by carrying out a detailed analysis of the data that was produced by the simulation tool. This fundamental difference will also be illustrated when describing the expanded IPV and data mining later in this chapter (section 5.4, 5.5).

5.2 Analysis types

The numerous requirements and considerations that must be addressed mean that building design is carried out in a multiobjective planning process. There are generally conflicting objectives and the planning approach will highlight a range of choices rather than one ‘optimal’ solution to the decision maker.

Donaldson and Mc Callum [1994] describe ten types of operations that designers apply in the design problem space and classify them in three groups:

Generate – select, create;

Evaluate – simulate, calculate, compare;

Decide – accept, reject, suspend, refine, patch.

From this it can be concluded that the analysis of performance predictions and the decision making based on this analysis potentially forms a large part of the general design process. Minter and Gale [1993] outline the complexity of a general system by specifying elements that affect system behaviour and analysis - boundary, communication, control, delay, environment, flow, information, structure, state and threshold are only few of the aspects listed. If we regard a building as an energy system, than these attributes also apply to a building. This makes the analysis as well as the decision making both complex and difficult.

The above description outlines the complexity a designer faces when applying simulation with the aim of enhancing the performance of a building design. Gero et al [1983] state four different design and performance relationships:

Design ? Performance

Predict the performance for a particular building design using simulation.

Performance ?   Design

Repeating the simulation process with different values for the design variables to obtain an indication for the best form of design.

Performance ?   Performance

Implications of choosing a certain level of performance based on one criterion on the performance that is then attained based on other criteria.

Design ?   Design

Implication of choosing a certain value for one design variable on the value that needs to be given to other design variables if acceptable performance is to be maintained.

Of the above relationships 'Design ?   Performance' is the original approach underlying a simulation analysis of a simulation model, but the 'Performance ?   Design' evaluation can also be identified as relevant in the context of the application of simulation in the building design process. ' Performance ?   Performance' and 'Design ?   Design' are also important but more difficult to implement and not vital for the application of simulation in the building design process.

As part of this research three different analysis types were specified which have to a degree parallels to the classification given by Gero. The different types identified are outlined in Table 5.1: (1) Problem identification (2) Causal analysis - what causes the problem? (3) Design guidance analysis - what can I do about it? Table 5.1 summarises aims and gives examples of the different analysis types. The text that follows the table discusses the issues in more detail.

Analysis type	***Aim***	***Example***
Problem identification	Identify insufficient performance.	Detect overheating problem.
Causal analysis	Find out what causes a problem.	Identify heat sources that cause the overheating, ideally combined with an analysis of heat loss paths in the building.
Design guidance analysis	Investigate different design options that could be applied to resolve the problem.	See how far it is possible to reduce the heat load in a space and/or what design changes can remove heat from a space more efficiently.

Table 5.1: The different analysis types

Problem identification is used for the performance confirmation of a design. Causal analysis and design guidance analysis will be employed in case the performance does not satisfy the expectations of the designer or the designer feels that a performance improvement could be achieved with design change(s).

5.2.1 Causal analysis

The possibility for improvement of inadequate building performance is significantly enhanced when the designer is provided with an understanding of the reasons for this performance. One possible approach to provide this information is analysis of the energy flows in the building. Another option is to remove design parameters (e.g. windows, ventilation rates, insulation levels) in different simulation runs in order to evaluate their impact on the building performance. Both approaches are discussed in the following section.

Analysis by energy flows

The evaluation of the energy flows that have been determined in a simulation run can reveal information such as the main heat loss paths from a building during the heating period or give an understanding of what heat sources cause an overheating problem in summer. Often this information is referred to as 'heat gains' and 'heat losses' that occur in the building. Different simulation tools provide the information as a standard output from a simulation exercise [LBNL 2002 a, NREL 2002]. Assessments of simulation tools also often include the question whether a tool is capable of providing such information or not [Schneider 1996]. Figure 5.1 shows different energy flow paths that occur in a building. Table 5.2 lists non-plant related building energy flow paths and their performance relevance. It does not include all the flow paths depicted in Figure 5.1 (e.g. it does not consider adjacent zone energy transfer) but focuses on those that predominantly influence the thermal energy and environmental performance of most buildings.

The following discussion evaluates (1) when it is possible to produce energy flow information and (2) how far this information is useful for the designer. It will be based on the energy flows in a single zone, representing a naturally ventilated room within a building with a window towards the south west and internal heat gains from occupants, lights and IT equipment (see Figure 5.2).

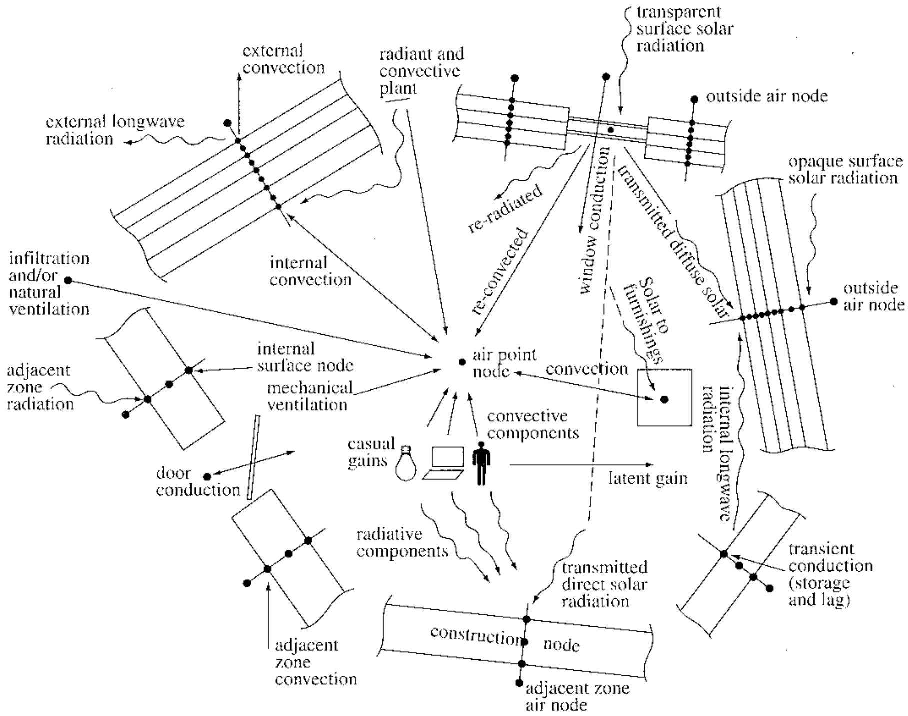


Figure 5.1: Building energy flow paths (from [Clarke 2001])

Energy flow path	*Design relevance*
Conduction through surfaces towards the exterior of the building.	Affects heating energy requirements of building.
Solar radiation entering the building.	Affects the heating energy requirements as well as summer comfort conditions/cooling requirements.
Internal heat gains in the space.	Affects the heating energy requirements as well as summer comfort conditions/cooling requirements.
Transient conduction (storage and lag).	Storage can reduce temperature swings (and hence peak temperatures) in the summer but can also increase the heating energy demands in winter.
Infiltration and/or ventilation.	Affects the heating energy requirements as well as summer comfort conditions/cooling requirements.

Table 5.2: Non-plant related building energy flow paths and their performance relevance

In order to specify energy flows in a building section it is necessary to define the system boundaries to be used in the analysis. Heat gains or losses are then defined as energy that passes this system boundary. Figure 5.3 shows two possible system boundaries for the case study – the inner or the outer faces of the surfaces that enclose the zone.

The effect of the choice of system boundaries on the energy flows that will be predicted can be illustrated on the basis of solar gains. If the boundaries were defined at the inner face of the surfaces, the system would capture solar gains in the form of solar radiation that passes through transparent constructions together with radiation and convection of solar radiation energy that has previously been absorbed by opaque or transparent surfaces (see Figure 5.4).

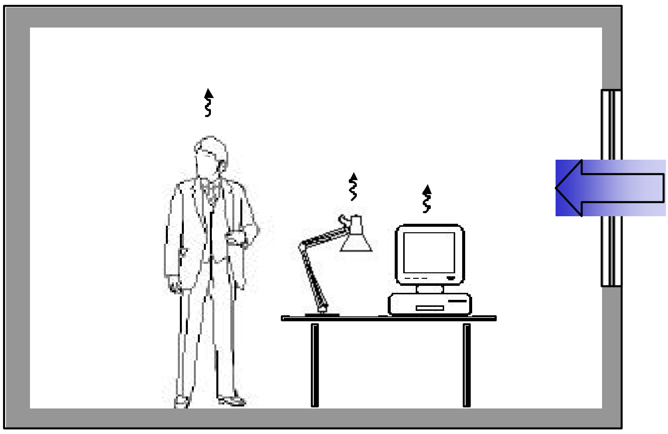


Figure 5.2: Single zone example

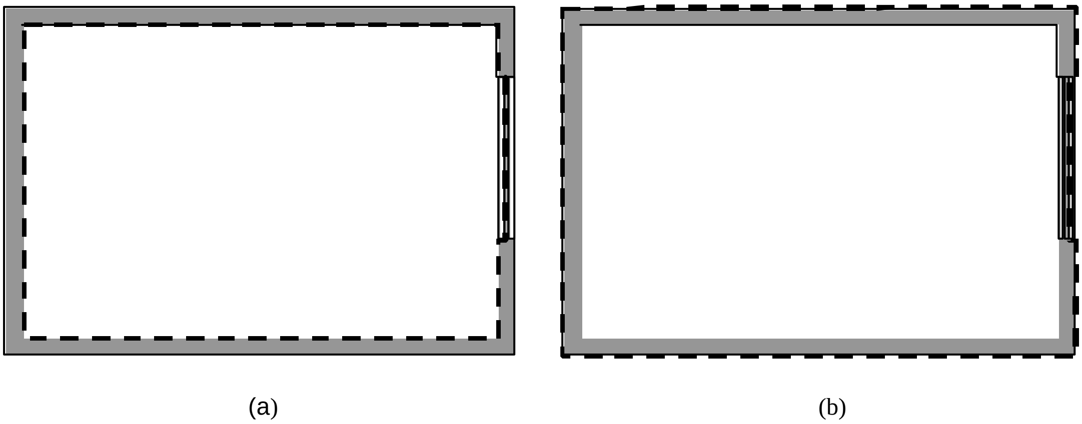


Figure 5.3: Possible system boundaries: (a) inner face of the surface as a system boundary (b) outer face of the surface as a system boundary

A second possibility is the definition of the external faces of the surfaces as system boundaries, in which case all the solar radiation that is absorbed or passes through external constructions would count as solar gain[1].

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[1] Apart from the two boundaries discussed here, intermediate specifications are also possible.

Defining the inner face of the surface as the system boundary has a number of pitfalls: solar radiation absorbed in the glass can cause discomfort because of higher surface temperatures[1], but after this definition this would not count as solar gains. In addition, solar radiation that enters the building through the window causes discomfort by heating up the surfaces which absorb the radiation ("storage effect") and also by heating up the air via convection from these surfaces. However, with the inner face being the system boundary only the latter would count as solar gain (See Figure 5.4).

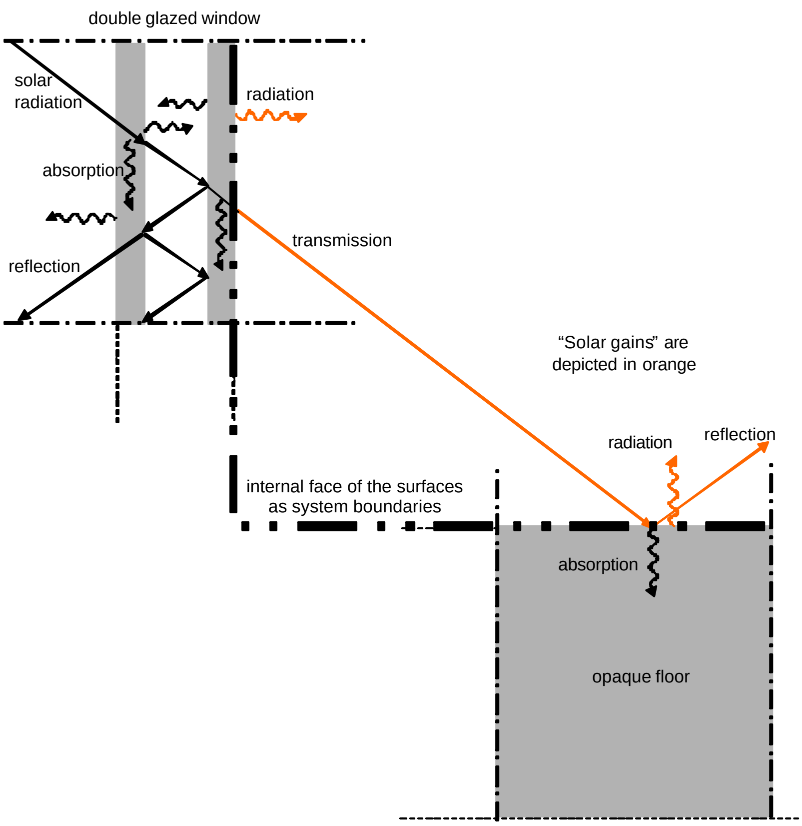


Figure 5.4: "Solar gains" when specifying the internal face of the surfaces as system boundaries

Defining the outer face of the surface as the system boundary would also be misleading, because any radiation absorbed in the system would already count as solar gain, e.g. radiation that is absorbed by an opaque façade construction but which never affects the internal environment.

[1] These effects have been shown to reduce the efficiency of solar control glass. Such constructions were designed with the aim of reducing direct solar radiation entering the building, but the effectiveness of the system is diminished by the increased surface temperature of the glass panels. This phenomena was reported by Janak [2002], who was involved into research of advanced glazing systems as part of the IMAGE research project.

Changing the focus to the transitional season reveals other complications. In the transition periods not all solar gains will be utilisable: although they will normally reduce the heat injection that is required from the plant in the early hours of the day this is not necessarily the case later in the day, when the ambient temperature rises. However, if the radiation is absorbed during the day by the construction it can reduce the heating energy consumption in the evening. From this discussion it becomes clear that it is far from trivial to capture the impact of solar gains in a way that is useful for the designer.

Analysis by parameter removal

An alternative to determining the energy flows in a building is the performance of simulation runs where one or a number of model parameters have been removed from the simulation model. This can either be parameters that relate to the simulation model itself (e.g. a window in order to understand how much its solar gains contribute to an overheating problem) or external parameters such as solar radiation. Energy 10 has incorporated this approach as a standard element of their analysis methodology [NREL 2002]. The program creates a number of design variants where it automatically removes parameters in a structured manner.

The information obtained from such a simulation run gives a clear indication of how far a window contributes to an overheating problem or reduces the heating energy consumption in a building. It also uses a terminology that the designer is more familiar with and can better relate to. This leads to the question why this approach is not applied more widely in other simulation programs. One reason that can be identified is the fact that the concept of parameter removal is not always as informative as in the case of a window. Energy 10, for example, offers the option to remove an external wall in order to evaluate how far it contributes to heat losses in winter. Such a concept is more difficult to understand.

Another issue is the complexity of advanced building simulation models, which makes it difficult to automate the change of a simulation model – a necessity if parameter removal is applied efficiently. As previously stated, simulation models in Energy 10 comprise no more than 2 zones and have only limited simulation features. Advanced simulation models programs are generally much more complex. In that case, the removal of a window from the simulation model can have implications on other model parameters (air flow model or the control for blinds of the window as just two examples). This makes the error-free application of this methodology a complex task[1].

This section has described the issue of giving the user an understanding of the reasons behind the behaviour of a building design. Findings from the discussion and associated references influenced the development of performance prediction analysis methods that will be introduced later in the chapter (section 5.4, 5.5).

5.2.2 Design guidance analysis

Having identified inadequacies in a building's performance (e.g. the above mentioned overheating problem) the designer will in most cases have a variety of options to improve it: reducing the window size (which might in turn affect natural ventilation options, which then would need to be accounted for *via data definition by the user*), fitting the building with brisoleil or blinds, increasing the ventilation rate, or a combination of several design changes. Making an appropriate decision is a non-trivial task. Different approaches have been identified in the past to improve this decision making process as discussed below.

Approach 1: Optimisation

One possible approach is to apply simulation in combination with optimisation methods in order to find optimum solutions for flexible design parameters such as insulation thickness, window size, ventilation rate, orientation, etc. (in optimisation terminology also called free or independent parameters).

With advanced optimisation algorithms, it is possible to define multiple optimisation criteria and search in a multidimensional space for the so-called minimiser [LBNL 2002 b]. Search algorithms normally do not require the creation (and hence simulation) of all possible design combinations, but apply strategies that allow the simulation of fewer combinations that can lead towards the optimum solution (the minimiser). One important aspect of optimisation is that the program might identify what is called 'local minimiser' – a good solution, but not the optimum one.

The Lawrence Berkeley National Laboratory (LBNL) has developed the software tool GenOpt, which automates the above described process [LBNL 2002 b]. The optimisation program can be used in conjunction with any simulation program that has text based input and output functions. When using the program the user defines the flexible design

[1] The application of DBMS in combination with simulation as described in chapter 4 is a useful contribution to enable such developments in the future.

parameters as variables in the simulation input files. The program then automatically creates simulation models by replacing the variables with appropriate values. In addition to the variables the user also has to specify their bounds (upper and lower value), the possible number of intermediate steps and the optimisation algorithm (the program offers a library of algorithms). The program also extracts all relevant results from the results library and uses them strategically in the further optimisation process.

Another research effort towards simulation based building optimisation was initiated with the ASHRAE research proposal "Building System Design Synthesis and Optimisation" [ASHRAE 1998]. In this case, the focus was on the plant side of the building design, and the aim was to automate the creation of design variants for complex plant models and to link them to optimisation algorithms that support the designer in decision-making.

Several publications describe case studies of how optimisation can be used in combination with building simulation. Wetter [2000] describes how optimisation was used to find optimum solutions for the orientation, window size and shading device transmittance of a building. Klemm et al [2000] describe an optimisation study which had the aim of arranging two buildings with constant geometric characteristics in a way that optimises wind flow around a building in order to increase the comfort conditions.

Other optimisation approaches go even further than the ones described above and intend to optimise a building not only with respect to its energy and/or environmental performance, but to address other issues such as cost, structural engineering or construction time. Examples are Marks [1997] who carried out a study with the aim of minimising the building cost (construction and material) and the heating cost for a building, and Mahdavi et al [1998] who address adjacency, thermal and acoustic issues.

Approach 2: Rule based design support

Another option for refining building performance is the integration of rules into the decision making process. In such a case the tool would tell the user that based on the results obtained from the simulation run it can be concluded that one or a number of design solutions seem appropriate to improve the design (theoretically this advice could be given after the causal analysis of the simulation results). Although such a concept seems useful it has not yet been integrated into dynamic building simulation tools, but is more commonly used in simplified design support systems. An example for such a tool is the BRECSU 77/98 software [BRECSU and Oscar Faber] described in section 1.3.

Another example for a rule based design support approach is described in Malkawi [1998], although the author only describes the general concept of deriving rules but does not implement it in software or illustrate it with a case study.

Discussion of design assistant vs. design automation

The tools and methods listed above all have the mutual aim of supporting the designer in generating a design solution with a better energy and/or environmental performance. However, they approach this objective in different ways. When applying optimisation or a Pareto analysis as Gero suggests, the aim is to provide the designer with the best design solution within the bounds that have been specified for the free design parameters. BRECSU 77/98, on the other hand, leaves the designer with more options by pointing out design directions that are appropriate with the design parameters that have so far been established. Duffy and Duffy [1996] specify the two essential design philosophies that define the outer boundaries within which such approaches can be positioned:

> *"The 'design assistant' philosophy considers a computer aided design (CAD) system as a designer's colleague, whereas the 'design automation' philosophy considers it as a designer's substitute"*.

The application of an *optimisation tool* is mainly based on the design automation philosophy: the designer defines the boundary conditions and the tool automatically creates the knowledge in the form of the optimum solution. The input of the designer in the decision-making is limited, and this has several implications. One is that the designer gains only limited insight into reasons behind the established design solution. However, this limited insight can be seen as an important benefit from the application of simulation in the design process. Providing designers with an understanding of the performance of the building with changes in design parameters and also reasons for this behaviour makes it easier to tie the performance predictions into the overall design process. Similar conclusions were also drawn by Pohl at al [2000], de Groot et al [1998] and Sariyildiz et al [1998].

Another important aspect is that designers benefit from this knowledge not only for this particular project, but also in projects they will carry out in the future. Duffy and Duffy [1996] describe this as follows:

> *"experience, which consists of knowledge generated from personal exposure to events and artefacts, presents one of the most powerful resources possessed by a designer"*.

In other words, such experience enables designers to preselect feasible design solutions and hence limit the number of design variants that will have to be assessed in the first place.

However, a negative aspect of the use of this 'black box' approach, which is inherent in optimisation tools, is that it can leave a designer with a feeling of not being in control of the design decision or understanding the reasons behind the design decision made. This is a situation many designers are not comfortable with.

Alternatively, *rule based approaches* give more flexibility to the designer, assuming they do not only provide one but a number of possible solutions. However, it is questionable whether such a rule based strategy can be universally applied. Every building is different (which is one of the main reasons for the development of building simulation programs in the first place), and it is therefore difficult to come up with general rules. Another factor is that in a particular design situation a design solution might be appropriate that has not been specified within the rules and in consequence it is very unlikely that the designer will consider this option. Hence, the increased design freedom that has been provided with the development of building simulation programs is removed by the introduction of restricting rules.

In summary every building is different and almost any design decision is part of a complex, multiobjective decision process and this should in consequence be as informed as possible. This makes it necessary to provide the designer with an understanding of the characteristics of the building, which is not achieved when applying simulation in conjunction with rule or optimisation based methodologies. The aim should rather be a tool that is a colleague to the designer and that in essence complements the designer's own skills, thus leaving the ultimate decision making, control and responsibility with the designer. The design guiding analysis methods that have been developed in this work are based on this philosophy.

5.3 Performance prediction analysis at the different design stages

Table 5.3 lists performance prediction analysis that are likely to be conducted at the different building design stages. It summarises findings which are discussed in more detail in the following sections 5.3.1 to 5.3.3.

Design Stage	Performance prediction analysis	Person potentially involved in performance prediction evaluation
Outline Design Stage	• Comparison of performance against recognized benchmarks[1]. • Information about reasons for poor performances. • Attention to plant efficiency, fuel type and emissions.	• Architects • Clients • Building services engineers
Scheme Design Stage	• Focus on typical or problem areas. • Analysis currently carried out by simulation expert, but assessment by non-experts architects would be desirable.	• Currently simulation and/or building services expert. Situation would be different once simulation is applied according to the SSDP (see section 3.3.2).
Detailed Design Stage	• Detailed technical analysis. • Only simulation experts carry out the evaluation.	• simulation and/or building services expert

Table 5.3: Performance prediction analysis at the different building design stages

5.3.1 Outline Design Stage

It was stated in section 3.3.1 that design decisions which are made at the Outline Design Stage are likely to fundamentally influence the energy and environmental performance of the finalised building design (e.g. will the building need air conditioning or not). It is therefore important to provide a general overview how a proposed building design is likely to perform (annual energy consumptions in the building, annual overheating hours, etc.).

The Outline Design Stage was previously also described as a time constrained design phase in which the typical user of a simulation program will most likely be a person with a limited knowledge in energy and environmental building design aspects (e.g. architect). The importance of design decisions at the Outline Design Stage makes it also not unlikely that the designer will present performance predictions obtained from simulation also to clients (e.g. to obtain the client’s view on possible cooling strategies) – clients are again a group of people who may not be experts in energy and environmental building design aspects. All this has consequences on appropriate methods for performance communication and analysis.

One is the requirement to show how the predicted building performance can be rated. This can be achieved by assessing the building performance against so-called recognised industry benchmarks.

Secondly it is important to provide an understanding for reasons behind the characteristics of a building (e.g. if a high cooling load occurs – what causes this heat built up).

A further important aspect of results analysis at the Outline Design Stage is the need to include details such as plant efficiency, fuel type and carbon emissions. Advanced simulation programs often only provide the energy loads of spaces within the building, which therefore have to be processed further to be meaningful – this is a task that cannot be expected from an architect or client.

This processing is especially of relevance when using simulation in conjunction with the Carbon Index Method or Whole Building Method of the Building Regulations [DTLR 2002 a, DTLR 2002 b].

5.3.2 Scheme Design Stage

At the Scheme Design Stage the simulation focus moves from a general evaluation of the building to a detailed assessment of certain areas in the building with the aim of enhancing their energy or environmental performance (see section 3.3.2 and 3.8.2) – to fully utilise building simulation it is therefore necessary to carry out a more in-depth analysis of the performance predictions obtained than this was the case at the Outline Design Stage. In terms of the overheating assessment quoted in the description of the Outline Design Stage this would be a detailed analysis of the influence of possible design changes listed in section 3.8.2 on the summer performance of the building. Nowadays, a simulation expert would carry out a simulation typical for the Scheme Design Stage (see section 3.3.2). This user group is likely to be at least to a certain extend familiar with the physical phenomena that underlie the simulation results which will support him/her in turning the performance prediction data obtained into useful information.

However, this situation would change if simulation at this stage becomes an application operated by architects. In that case the limited background of the user would have to be taken into account and this would need to be reflected in the way performance predictions are analysed (comprehensible to a person who is not an expert in energy and environmental design issues).

5.3.3 Detailed Design Stage

At the Detailed Design Stage simulation becomes very technical. It is used to assess complex design aspects such as the layout and control of a natural ventilation system. The

[1] Only appropriate benchmarks can ensure that simulation predictions are put into a meaningful context. Hence the further integration of simulation within the building design process can benefit from research in this area.

thorough performance prediction analysis outlined above for the Scheme Design Stage is therefore again of particular relevance at the Detailed Design Stage.

Another consideration is that during the different design stages the simulation model detail will have constantly increased. At the detailed design stage the building representation is therefore for many design projects more complex than at the initial design stages (e.g. due to the inclusion of air flow network networks). These issues can make the analysis of the performance predictions and the resulting decision making significantly more complex. The person carrying out the analysis will however have a background in energy and environmental building design considerations. It is therefore (as at the Scheme Design Stage) not important to provide the user with an analysis tool tailored towards the requirements of a non-expert.

So far this chapter has dealt with concepts how knowledge could be extracted from simulation result data sets as well as an overview of performance prediction analysis which are likely to be carried out at the different building design stages.

The following sections describe research into two tools this analysis at two different design stages:

- An expanded Integrated Performance View (IPV) for the Outline Design Stage and
- The introduction of data mining for the Detailed Design Stage.

The research utilised findings and conclusions described in the first part of the chapter. Reasons for the focus on the Outline Design Stage and Detailed Design Stage were discussed in section 3.10.

5.4 Expanded concept for an Integrated Performance View (IPV)

This section describes additional components that have been integrated into Integrated Performance Views (IPVs, see section 2.3.6) to make them more suitable for building analysis at the Outline Design Stage.

5.4.1 Introduction

The concept of IPVs was already described in section 2.3.6 of chapter 2. It was stated that IPVs are quick and easy to generate and that their standardised output of several performance criteria makes them especially suitable for non-simulation experts because it encourages the evaluation of the building performance in a holistic manner. Both were described in section 5.3.1 as requirements for the Outline Design Stage. However, currently

IPVs still have limitations that constrain their applicability at this phase of the building design: (1) they do not provide benchmark figures that help the designer understand the meaning of a performance prediction obtained, (2) they only indicate the performance of the building but give no reasons for this performance (e.g. they only indicate heating or cooling energy consumptions but do not give reasons for these energy requirements) and (3) they give no insight how the performance predictions have been derived (e.g. what was the energy source based in which carbon emissions were calculated). The following sections (5.4.2 to 5.4.4) describe findings from research carried out to address these issues.

5.4.2 Benchmarks

Benchmarks are not applied in the context of dynamic building simulation are provided with tools such as the UK Best Practice Programme [EEBPP 2002], or the Toolkit software [Doggart 1995].

Energy 10 has another type of benchmarking system in which it applies all possible energy efficiency measures to a specific building geometry and type. It is then possible to evaluate how design variants compare to the benchmark derived from the original simulation model. Despite the fact that it can be seen as a motivation to show what can be achieved the benchmark does give indications out how the building performance can be rated in comparison with other buildings of this type.

Benchmark data can be sourced from publications such as the Best Practice Programme or Field [1997]. However, benchmark figures are still not available for all building types [Jones 2001]. Prison buildings are an example for one type not included (this observation was made by Badger[2002], a senior project manager for several prison projects carried out by the architectural design company were a considerable part of the research was conducted).

5.4.3 Move from energy loads to overall energy consumption of building

Unless the user specifies a plant network the ESP-r system [ESRU 2002] only determines room heating and cooling loads. System inefficiencies are only taken into account if the designer carries out detailed plant modelling, which is not applied on a frequent basis due to the complexity involved in the creation of a plant network. It also is not equipped to calculate the energy requirements for mechanical ventilation system. However, with a benchmark exercise at early design stages it is important to take these aspects into consideration. For this purpose a new IPV function was developed, a spreadsheet that determines plant inefficiencies and ventilation requirements for a building. The calculations are based on Building Energy Code 2 (Energy demands for air conditioned buildings), developed by the Chartered Institution of Building Services Engineers [CIBSE 1997]. The code assumes a sinusoidal curve for climatic conditions and simplifies aspects such as internal heat gains or ventilation rates. This can result in considerable inaccuracies in the predicted room load which form the basis for the plant calculation. Using simulation allows the more accurate determination of the room loads. The author carried out the research into how to use simulation to determine these loads so that they can form the basis of an evaluation with the Building Energy Code 2 jointly with an experienced building services engineer within the test bed company.

5.4.4 Descriptive comments

Within this research, IPVs have been extended to provide description and comments about the performance predictions they report. These have been included in response to the fact that the designer who uses the IPVs at the early design stage is not familiar with energy and environmental issues to the same degree as a simulation expert. An example would be the prediction of CO_2 emissions from the building. The emissions are influenced by the fuel type that has been used. This information should therefore be included in the new extended IPV.

5.4.5 Causal Analysis

It was indicated in section 5.2.1 that with advanced simulation programs it is difficult to implement a *parameter removal analysis* and that the definition of *energy flows* is not a straightforward task. However, an approach was specified to show how energy flows can still be utilised to help the designer understand the behaviour of the building.

Heating season

At times when the building requires the injection of heat via the plant systems, heat loss may be specified as energy that conducts through the external building envelope or energy that leaves the building via ventilation. Heat gains include any radiant and convective internal heat gain, and solar gains that enter through transparent constructions.

This information enables the designer to answer questions such as reasons for heating requirements in the first place (e.g. what is the influence of larger windows on the overall heat loss) and in how far solar and internal gains contribute towards these heating energy requirements and hence do not need to be met by the plant.

Heat Losses	Heat Gains
• Heat loss through building envelope; • Heat loss by ventilation;	• Internal heat gains; • Solar gains that enter the room through transparent constructions;

Table 5.4: heat gains and losses in the heating season

Cooling season/periods with internal temperatures above a user specified level

Heat gains in this period will occur from solar gains or internal heat gains. Indicating to the designer which of these heat sources occurs in cooling periods or times when the temperature goes above a certain level gives the designer insight how it is possible to reduce the cooling load or improve the comfort conditions in a space. In this period heat losses are more difficult to quantify due to storage effects in the building fabric. Hence heat gains are the only energy flows that are provided to the designer.

Heat Gains
• Internal heat gains • Solar gains that enter the room through transparent constructions

Table 5.5: heat gains in the cooling season/periods with internal temperatures above a certain level

The analysis described above is a rather crude assessment that provides only limited insight into the behaviour of a building. Nevertheless, the purpose of the performance analysis at the Outline Design Stage is to understand key reasons behind the performance of a building, which can be achieved with this kind of analysis.

Examples of cases where the analysis could provide misleading information are outlined below:

- Solar gains are simplified because they only consider transparent and not opaque constructions. For a modern building with insulation layers integrated into the building envelope this will normally be sufficient to understand the impact of solar gains on the summer performance of the building. However, this approach can be inappropriate e.g. for a storage building with an uninsulated roof, where high temperatures can occur under the roof due to solar gains from this opaque construction.
- A related limitation could become relevant if the analysis technique was applied for a building located in a climate zone unlike the British weather conditions. In hot

climatic areas, for example, solar gains absorbed by an uninsulated opaque building envelope could have a significant impact on the performance.

5.4.6 Example of an expanded IPV for the Outline Design Stage

Figure 5.5 shows an extended IPV for the Outline Design Stage which includes the additions discussed in the previous section, with the exception of causal analysis which is presented separately.

5.4.7 Discussion of expanded IPV

The last sections have described how the concept of IPVs was expanded to make them more suitable to communicate at early building design stages performance predictions obtained from a simulation exercise to non-simulation experts.

The inclusion of benchmark data adds more meaning to the performance predictions because it shows how a building compares to industry standards. This development has been carried out in response to the fact that such knowledge cannot be expected from architects (and also clients), who are very likely to use the IPVs.

The specification of the overall building energy consumption in the IPVs was also considered an important contribution for the use of simulation at early building design stages. By only providing room loads the person viewing the performance predictions obtains an incomplete picture about the building performance.

Also, in light of a potentially increased application of simulation to check compliance of a building under the Whole Building Methods and the Carbon Emission Calculation Method as specified in the new Building Regulations the determination of the overall building energy consumption should be possible as part of a simulation exercise, in particular because this element of the Building Regulations was identified earlier (1.6.4) as a potential catalyst for the use of simulation within the building design process. Without providing this assessment option an opportunity would be missed to increase the use of the tool and hence promote its capabilities in general.

Providing causal analysis facilities has the advantage that the outcome of a simulation analysis can be better used as part of the decision making. Reasons for the building performance are indicated, informing the person viewing the performance predictions what design changes have a potential to improve the building performance.

Whole Building Integrated Performance View (IPV)

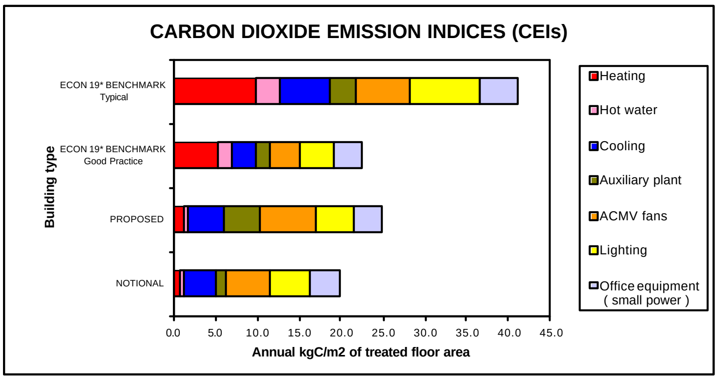
ANNUAL EMISSION OF CO2 (CEI) - [kgCarbon/m2 treated floor area]

Building type	Heating	Hot water	Cooling	Auxiliary plant	ACMV fans	Lighting	Office equipment (small power)	Total
NOTIONAL	0.8	0.5	3.8	1.2	5.3	4.9	3.4	19.8
PROPOSED	1.3	0.5	4.3	4.3	6.8	4.4	3.4	24.8
ECON 19* BENCHMARK Good Practice	5.2	1.7	3.0	2	3	4.1	3.3	22.4
ECON 19* BENCHMARK Typical	10.0	2.8	5.8	3	6	8.5	4.5	41.2

* - The figure shown for ECON 19 are from Table B3 of the Energy Consumption Guide 19 with the Carbon Emission Factors for Gas taken as 0.053 (kgC/kWh) and Electricity taken as 0.113 (kgC/kWh) as Table 1 of BRE digest 457. The factors were also applied for the simulated buildings.

Energy sources

Heating	Electrical
Hot water	Electrical
Cooling	Electrical
Auxiliary plant	Electrical
ACMV systems	Electrical
Lighting	Electrical
Office Equipment	Electrical



Note: THE FOLLOWING ENERGY CONSUMERS HAVE BEEN IGNORED FOR EACH OFTHE BUILDING TYPES: **HUMIDIFICATION,CATERING,LIFTS,COMPUTER ROOMS AND ELECTRICAL REQUIREMENTS OVER AND ABOVE NORNAL SMALL POWER**

Figure 5.5: Example of an expanded IPV for the Outline Design Stage

5.5 Data mining

The last section described steps taken to tailor an IPV towards the requirements of the *Outline Design Stage*. It was explained that the aim of expanded IPVs is to enable a person with a limited knowledge in energy and environmental building design to carry out an adequate analysis of performance predictions obtained from a simulation exercise. The remaining part of this chapter now introduces data mining as a novel concept for the detailed analysis of performance predictions at the *Detailed Design Stage*.

Section 5.1 outlined that the analysis of performance predictions at the Detailed Design Stage data (which would in that design phase be obtained from the *fully functional ESP-r interface* [ESRU 2002]) differs significantly from the one at the Outline Design Stage. Rather than giving non-simulation experts a general indication of the likely behaviour of a building design the aim of the analysis is now to enable simulation and/or building services experts to obtain an in-depth understanding of the characteristics of the building design. Opposed to the Outline Design Stage it is hence not possible to specify what data should be how presented (e.g. energy benchmarks, frequency distribution of temperatures), but the person carrying out the analysis will have to be provided with a tool that allows a flexible and in-depth analysis of the data obtained from the simulation exercise.

Section 5.5.3 will illustrate problems that can occur when trying to perform this task. Data mining looked as a promising tool to overcome this barrier. The following sections describe research carried out to see in how far this is actually the case.

5.5.1 Introduction

At the beginning of this section a general introduction to the concept of data mining and alternative analysis techniques is given, followed by an overview of the different data mining techniques. It is then shown how data mining can enhance the analysis of performance prediction obtained from building simulation. Finally there is a discussion of the general suitability of data mining for use in conjunction with building simulation and within the building design process.

5.5.2 What is data mining?

The amount of data available nowadays to scientists, engineers and business managers is vast. Almost all of this data is available electronically, stored in databases and commonly connected via computer networks, intranets or the Internet. This abundance of data has been described as a *data rich but information poor* situation and has stimulated research into better ways of examining the data. Data mining is one of the tools that resulted from these efforts. This has the aim of enabling *the extraction or mining [of] knowledge from large amounts of data* [Han and Kamber 2001].

5.5.3 Why use data mining in conjunction with dynamic building simulation?

The amount of data generated from a simulation run can be considerable, depending on the number of days simulated. Different users of simulation programs have varying preferences for the duration of a simulation, varying from a typical day to annual simulations, depending on what is believed to be required to understand the behaviour of the building. Many practitioners approach the assessment of a building by performing simulations that cover long periods, even up to a year (Donn [1997] comes to this conclusion after carrying out a survey among designers who use simulation programs, Ho [1999] draws the same conclusion from her experience as a simulation consultant). It is probable that a move towards longer simulation periods (and also a larger number of design variants) will also find a wider application with the development and application of IT equipment with faster data processing and larger storage capabilities. This increased data quantity obtained from simulation runs widens the gap between the generation of data and understanding of it, making the already non-trivial task of analysing building performance predictions and understanding the reasons for a particular performance even more difficult. The following example illustrates this issue.

Figure 5.6 shows the results of an air flow analysis that was carried out for one zone of a simulation model over a two month period. It is straightforward to extract typical and extreme values for the air change rate in the zone, but specific questions are more difficult to answer, for example:

- Under what conditions does the air change rate in the building exceed 6 air changes per hour?
- How does wind speed and direction affect the air change rate in the zone?
- Under what conditions do comfort problems due to draughts occur at ventilation openings?

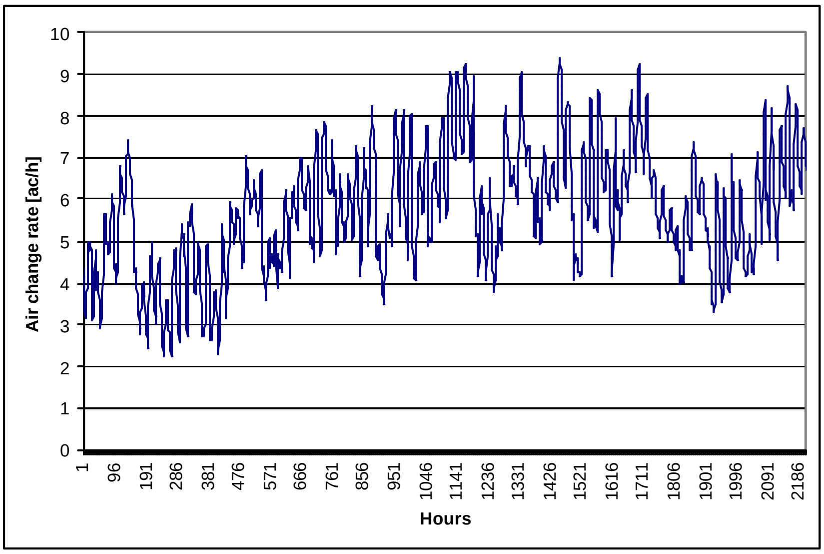


Figure 5.6: Air change rate in a zone over a three month period

All of the above questions involve an analysis of several parameters (air change rate, air flow rate through an opening, wind speed, wind direction) which can change significantly during short periods. Patterns that give answers to the questions stated above are normally extracted in manual processes by viewing tabular or graphical data displays. Automating this procedure by combining the results analysis with data mining was identified as a useful contribution for the integration of simulation into the building design process and was the incentive for the research described in this section.

5.5.4 Alternative analysis methods

Description of methods

The search for knowledge (or patterns) in data is not a new concept, but was of interest even when data was stored in non-electronic form. Examples for pattern finding tools in electronic data sets that have been developed in the past are query functions of DBMS as described in section 4.4.

Another example for a pattern finding analysis technique is a scatter plot graph of two variables. Figure 5.7 shows such a graph displaying heat extracted from a building by means of cooling versus the ambient temperature conditions.

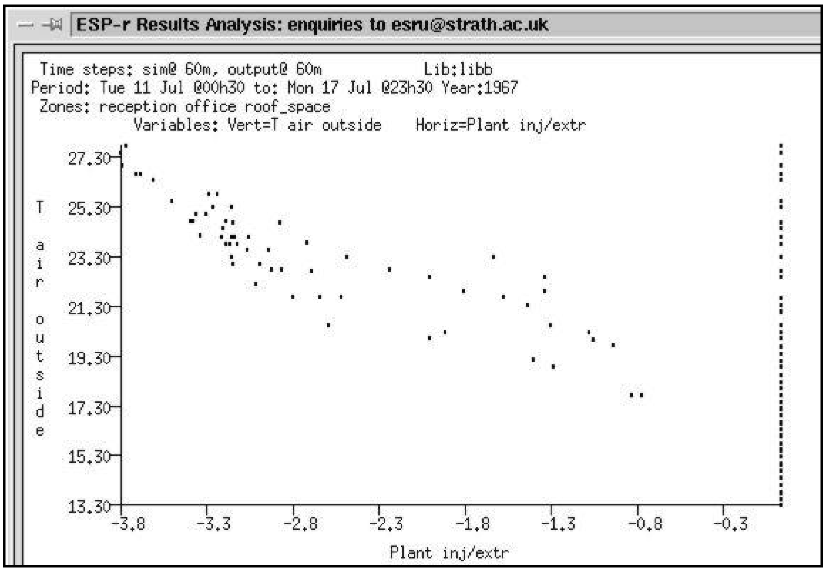


Figure 5.7: Scatter plot graph of the full functional ESP-r system

Apart from a graphical analysis it is also possible to carry out a regression analysis for two variables. A linear least square analysis evaluates how far data deviates from its least-square line - the least-square line is the line that fits best the distribution of data points (see Figure 5.8). In the case of a strong linear correlation, the points lie close to the least-squares line and the sum of square distances between the points and their corresponding line values is small.

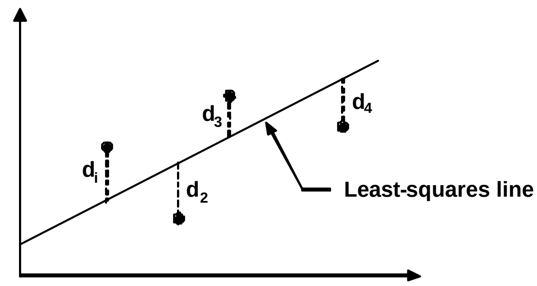


Figure 5.8: Least-squares fit

Nonlinear regression analysis applies the same principal as a simple linear least square analysis but under the assumption that the variables have a non-linear correlation. Multiple regression analysis is an extension to simple linear regression analysis when more variables are added.

Uncertainty analysis techniques such as factorial analysis are another possibility for the evaluation of correlation between variables. Variable(s) under consideration are changed in multiple simulation runs and it is evaluated to what extent these changes affect the building performance. By this means it is possible to determine the design parameters that have an impact on the behaviour of the building.

Discussion of methods

All of the above listed analysis techniques are evaluated in Table 5.6 for their functionality and ease-of-use. The following section describes and discusses different aspects in more detail.

	Fast and interactive analysis	**Numerical quantification of findings**	**Possibility of multiple variable analysis**	**Easy to use software implemen-tation**	**Visualisation of findings**
Visual analysis (e.g. scatter plot)	+	-	0	+	+
Regression analysis	+	+	0	-	0
Uncertainty analysis	-	+	+	0	0
Data mining	+	+	+	+/0	+/0

Table 5.6: Rating of different analysis techniques
(+ yes, - no, 0 neutral)

Visual analysis like a scatter plot graph is easy to carry out and can reveal useful information. However, the analysis does not provide numerical quantifications and the analysis of a larger number of variables can be difficult.

Regression analysis supports the analysis of data correlation by giving additional numerical information such as the correlation coefficient. Software tools which can be used to carry out the analysis (e.g. Maple [Waterloo Maple 2002] or MATLAB [MathWorks 2002]) are powerful but can also be complex, rather difficult to operate and often require from the user statistical background knowledge [Swain 2001, Thomas 1997, Lionheart Publishing 2001] .

Uncertainty analysis requires first the specification of the variables under consideration. After that the uncertainly is evaluated by means of multiple simulation runs. This process can be time and CPU intensive. Hence the approach does not allow the interactive analysis of a building design by focusing on different variables in turn within short time periods.

Data mining provides (at least to a certain extent) all of the requirements outlined in Table 5.6. It is possible to quickly and interactively analyse the data. Many of the analysis processes are automated or at least semi-automated; hence the analysis can be carried out by a user with a very limited understanding of the underlying analysis techniques. Findings are supported by both numerical quantification and visualisation and rules also often help the designer to understand patterns within the data set. The software packages also allow the analysis of multiple variables and can also evaluate data. The evaluation of different data mining tools and techniques later in this chapter (section 5.5) will support these statements.

The boundary defining whether a certain software tool is a mathematical or statistical application or whether it is a data mining tool is often difficult to determine, especially since the development of the latter is to a significant extent based on the former. Clustering is introduced in section 5.5.12 as a data mining technique but has already been applied for many years in data analysis. Some software tools that were initially developed for statistical purposes now also claim to have data mining capabilities [e.g. SSPS 2002] - Littell [2002] also observes this trend.

5.5.5 Current application of data mining in the building design process

Data mining has to date found only limited application in the field of building simulation. One example of a successful application in the built environment is described in Ashford [1998], where the tool was used for the identification of plant performance factors, highlighting potential energy savings in the order of 25%. The study was carried out with the aim of using data mining for the extraction of knowledge from the large volumes of data which are accumulated by Building Management Systems (BMS). The research was carried out on three buildings: a large prestige air conditioned office, a nursing home and a high school. All had known operational problems that remained unsolved until data mining provided a better insight into the plant operation. Examples of knowledge that was extracted are the fact that simultaneous heating and cooling occurred when the re-circulation damper had a certain opening position and correlations between simultaneous heating and cooling at times of return air temperature above 35ºC and the fresh air temperature above 9ºC.

Examples for other research into the application of data mining in the building design process is described in Simoff and Maher [1998] who suggest multimedia data mining from a variety of data sets (text files, drawings, etc.) to support the building design process. Another example is given in Smith and Maher [2001], who investigate the use of data mining in conjunction with 3D virtual environments. Both research publications suggest that data mining can be facilitated to support the generation of better building designs. Still, the manner the application of data mining is described in the publications is rather complex, making it unlikely that to date the approaches described could find routine application within the building design process.

Another example for the emerging recognition of the benefits that data mining can bring to the building design process is the fact that the Faculty of Architecture at the University of Sydney teaches data mining as part of their graduate degree courseworks.

Despite the fact that many applications of data mining occur in the area of business applications such as marketing or sales [Witten and Frank 2000], data mining also finds application in other, often more technical areas. One example is data mining in biomedical and DNA data analysis, where the researcher also faces a situation where large data sets have to be searched for patterns [Han and Kamber 2001]. Another example is load forecasting for the electricity supply industry, where data mining can be use to detect correlations between climatic conditions and other characteristics that influence load demands, for example the time of day or week [Witten and Frank 2000]. Again this is a situation where the amount of data in combination with the complexity of potential correlation makes it difficult to manually determine these patterns from the data set.

5.5.6 The data mining process

Different data mining techniques have been developed and are described, discussed and evaluated in the context of building simulation later in this chapter (section 5.5.11 to 5.5.13).

This section gives a more general overview of the data mining process. Figure 5.9 shows the different steps involved in the extraction of knowledge from data (after [Han and Kamber 2001]):

1. Cleaning of the data to remove noise or missing data[1].
2. Integrate the data into data warehouses – this is applied if multiple data sources are combined.
3. Selection of task relevant data.
4. Applying data mining to extract patterns from the data - here the user can choose between the different techniques which will be described later (section 5.5.11 to 5.5.13).
5. Evaluate the patterns that the data mining tool has discovered.
6. Present the significant patterns to the user.

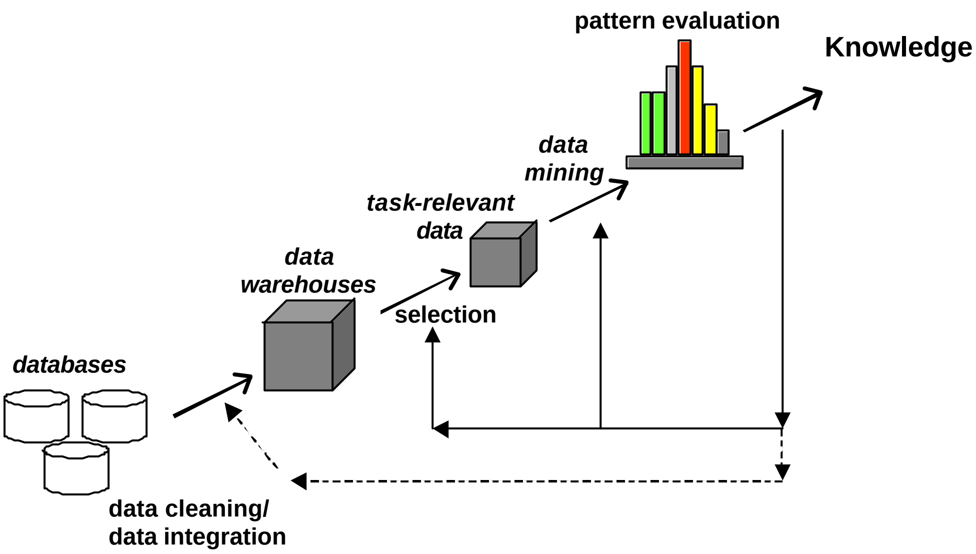


Figure 5.9: The process of extracting knowledge from data (based on [Han and Kamber 2001])

5.5.7 The different data mining philosophies

Data mining can be conducted in different ways. One distinction is between ***descriptive*** and ***predictive*** data mining. Predictive mining uses the patterns discovered in a complete dataset to predict the behaviour of one or several target variables from a partial dataset. An

[1] This step is not really required when using data sets that have been generated from simulation programs. However, noise and missing data is an important aspect in the development of new data mining algorithms, because accurate data cleaning cannot be guaranteed and might cause "incorrect" knowledge.

example would be two data sets A and B with data set A containing for different households' energy use data along with information such as floor area, house type, number of children, income, etc. Data set B contains the same information without the energy use information. Data mining could now be used to predict the energy consumption in data set B based on patterns discovered in data set A.

Although it is generally also possible to use predictive data mining in conjunction with building simulation (e.g. how will the comfort conditions in the building be affected by an increased ambient temperature that is not contained in the climate used in the simulation) the application of this data mining technique is not really feasible because simulation will perform this task much more accurately – i.e. would be much more appropriate to change the climate set.

Descriptive data mining uses a different approach. It discovers patterns in a data set and communicates them to the designer. An example for descriptive data mining is the analysis of an overheating problem and the extraction of conditions under which high temperatures occur in a building.

Another differentiation can be made between the ***black box*** and ***transparent box*** approaches: in a black box approach the reasons behind the findings are incomprehensible (as in the information that is obtained from an optimisation tool). The transparent box approach can reveal patterns, allowing the user to examine and reason about the pattern and use it to inform the decision process – in a similar way as was described for the design assistant philosophy for CAD systems (section 5.2.2).

5.5.8 Data definition in data mining

Variables and instances

All the data mining techniques described in this work require input data in the DBMS format described in chapter 4[1] (attributes and instances). Publications and software tools refer to attributes also as "fields" [IBM 1999 b], "variables" [Salford Systems 2000] or "aspects" [Witten and Frank 2000] and to instances as "tuples" [Han and Kamber 2001]. This thesis still uses the word "instance", but uses "variables" instead of attributes, because it is a terminology that fits better into the general philosophy and processes of a data mining exercise.

[1] Other data mining techniques mine in text databases or even the Internet and have different data requirements.

Categorical and continuous data

The data mining techniques introduced use two different data groups: ***continuous*** data and ***categorical*** data. Continuous data items are numeric values - temperatures or solar radiation data are examples[1]. Categorical data items take values from a prespecified, finite set of possibilities – examples are window size in a room (small, medium, big) or occupancy definitions (occupied, non-occupied).

Generally it is possible to convert a continuous data type into a categorical data type by grouping all records that fall within certain boundaries into one category. This has however the implication that the data mining tools will not know about neighbouring categorical data sets. An example is an internal temperature data set that has been grouped into categories. If one category ranges from 20 ºC to 22 ºC and the next one from 22 ºC to 24 ºC then 21.9 ºC to 22.1 ºC would be placed in independent categories. However, some data mining algorithms would use during the mining process the information that the two temperatures are very close [Witten and Frank 2000].

A special aspect of continuous data obtained from simulation exercises is the 360° angle with which wind directions can be specified. When performing a data mining session it will be assumed that 5° and 355° are not related at all, although they define nearly the same wind direction. The user has to be aware of these issues when analysing the knowledge generated. However, this does normally not cause major problems in the interpretation of data mining results analysis (as a later example will show – see section 7.2.3).

5.5.9 Different data mining techniques

This section describes the theoretical concept behind data mining techniques that fall into the group of ***transparent, descriptive data mining*** – were patterns are extracted from the data sets and displayed to the designer. For this purpose a classification is used as specified by Han and Kamber [2001]. After that different software tools are introduced that apply these techniques, followed by a discussion of the different techniques and also the tools.

Association Mining

Association mining discovers association rules that occur frequently together in a given set of data. Examples of association mining rules are:

[1] Continuous data items can again be further distinguished into ordinal, interval or ratio quantities. However, such distinctions are not possible in common data mining tools and were in consequence not included in the discussion.

wind speed (4-6) Ù wind direction (270-300) Þ air change rate (4-6)

or

air change rate (4-6) Ù solar radiation (200-400) Þ resultant temperature (26-28)

Wind speed is given in [m/s], the wind direction in [°], the air change rate in air changes per hour and the resultant temperature in [°C].

Along with the rules the Association Mining analysis also contains information about the interestingness[1] of a particular rule. What this means is explained later (section 5.5.11).

(Tree) classification

Classification analysis intends to identify, as with the association mining technique, rules from the dataset it investigates. The difference is that association mining aims to discover any correlation between the different variables of the dataset, whereas classification mining only discovers rules that relate to one particular variable. In consequence, the user has to specify a "target" [Salford Systems 2000] or "active" [IBM 1999 b] variable in the process of setting up the mining task - for this reason a classification analysis is also sometimes referred to as "supervised learning". Example rules that could be obtained from the classification mining technique with air change rate as a target are:

wind speed (4-6) Ù wind direction (270-300) Þ air change rate (4-6)

or

wind speed (2-4) Ù wind direction (30-90) Þ air change rate (0-2)

Classification mining results are often displayed in a tree format and are then referred to as 'three classicisation'. Such a display type has also been investigated a part of this research, hence the term is also used later in this thesis.

Clustering

The output of a cluster analysis is different from the rules created by the association or classification mining technique. In a cluster analysis the data is grouped with the aim of placing instances in segments in a way that maximises the similarity between instances of

[1] The terminology 'interestingness' is used by Han and Kamber (2001) and is also used in this thesis. The word stands for rating how interesting a pattern is.

one segment and minimises the similarity between the instances of different segments. Figure 5.10 shows the results from a two-dimensional cluster analysis. The analysis can however be carried out in any dimensional space.

Outlier analysis

Normally data mining is used to extract typical patterns from a data set, e.g. under which conditions a room will overheat. However, a dataset may also contain instances that do not comply with these typical patterns. These instances are called outliers. Normally mining algorithms regards these instances as noise or exceptions and will give them low priority in the mining process. However, in certain areas this information can be useful, as e.g. for fraud detection in insurance data sets. Outlier analysis techniques have been created to find such instances. However, when using data mining in conjunction with simulation data analysis the designer is primarily interested in obtaining a general understanding of the behaviour of the building. Focus on exceptional patterns is only of secondary relevance (if at all). Outlier analysis is hence not further discussed in this thesis. It should however be emphasised that a potential exists to use such analysis techniques in the built environment for tasks such as fault detection in HVAC control systems.

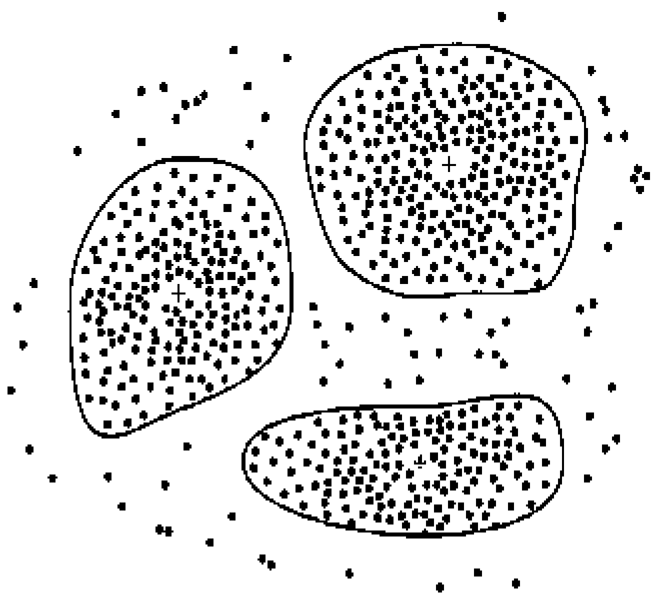


Figure 5.10: A two-dimensional cluster analysis (from [Han and Kamber 2001])

Evolution analysis

Evolution analysis (or time series analysis) describes variables' behaviour over time and is an interesting concept that could be used for the evaluation of phenomena such as storage effects. However, it is rarely incorporated in data mining tools and has hence not been included in the evaluation.

5.5.10 Evaluation of data mining programs

Many data mining tools have their origin in research applications that have been extended to commercial applications [Cabena 1998]. The evaluation of data mining tools in the context of building simulation included three software packages, of which one was a research application (Weka) and two were commercial packages (Intelligent Miner for Data and CART). By evaluating software programs from both ends of the application spectrum a more complete evaluation of data mining in relation to building simulation could be carried out.

Weka

Weka (Waikato Environment for Knowledge Analysis) was developed by the University of Waikato in New Zealand. It is research software and is downloadable from the Internet [University of Waikato 2002]. The program contains a large number of mining algorithms and also includes methods for data pre- and post-processing and for the evaluation of the results obtained from the mining sessions.

Intelligent Miner for Data

The Intelligent Miner for Data[1] [IBM 1999 b] was developed by IBM at the IBM Almaden Research Centre and can be used as an additional component of the IBM DBMS software DB2. It is based on work carried out as part of the QUEST research project, which had the aim "to develop technology to enable a new breed of data-intensive decision support applications" [Agrawal et al 1996]. The program is a suite of statistical, pre-processing and mining functions, which include association, classification and clustering methods. The program also has incorporated visualisation tools that communicate discovered patterns to the user of the program. The Intelligent Miner for Data is available free of charge for research purposes [IBM 2002].

[1] Later in this thesis referred to as the Intelligent Miner

CART

CART [Salford Systems 2002 b] is an acronym for Classification and Regression Trees. The program was developed by Salford Systems in San Diego, California. The program produces a tree structure that can be interrogated by the program user. CART is downloadable from the Internet for trial purposes [Salford Systems 2002 b].

Pre-selection of software

The three programs were evaluated for their functionality and ease-of-use (see Table 5.7). This included an investigation of the documentation of the software, the background knowledge the user needed about the different mining methodologies when setting up a data mining model and how the results were presented.

It turned out that with both the CART and the Intelligent Miner the user was able to create results after having passed an initial period of studying the documentation and software functionalities. Weka was more difficult to comprehend. The software is a research software and offers the user a much higher degree of freedom, which often requires specific background knowledge by the user. Other disadvantages of the Weka system, compared with commercial packages, were its limited visual communication of the patterns that were found in the datasets, and its less intuitive functionalities and operations.

Despite the fact that increased flexibility for the user can result in better findings from the data mining sessions, its disadvantages meant that the Weka system was not suitable for use in combination with simulation in the building design process. In consequence it was not further evaluated in the research.

	Documentation of software functions	**Accessible for non-expert**	**Intuitiveness of software**	**Visualisation of findings**
Weka	-	- -	- -	0
Intelligent Miner	+	0	0	+
CART	+	0	0	+

Table 5.7: Rating of software tools
(++ very easy/good, + easy/good, 0 neutral, - difficult/limited, -- very difficult/limited)

The following section describes in more detail the two remaining software tools and the data mining techniques that have been assessed in the research. The description is based on a very simple case study that analyses the impact of direct solar radiation and ambient air temperature on the resultant temperature in a single room[1].

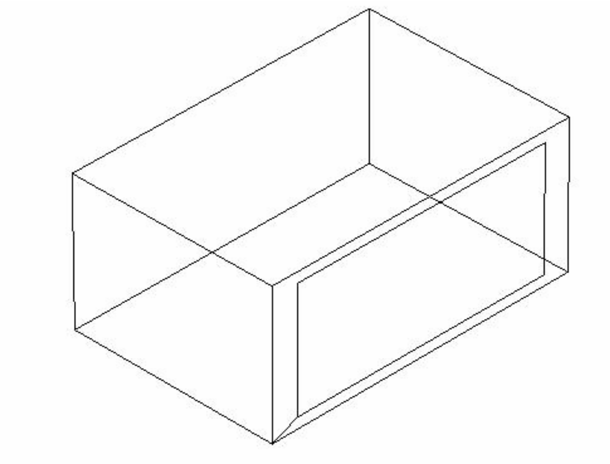


Figure 5.11: Image of the simulation model

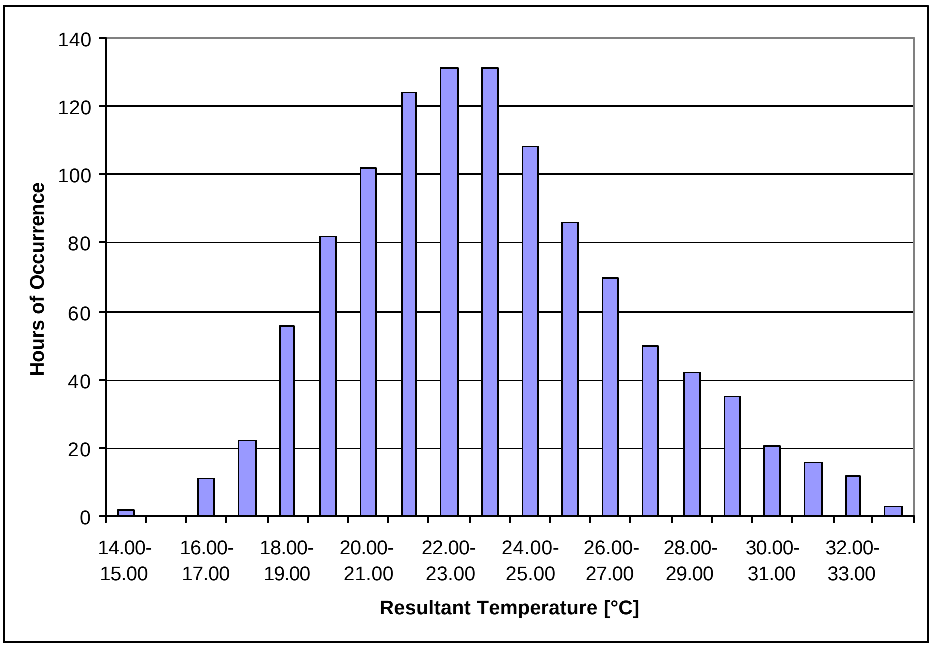


Figure 5.12: Frequency binning of resultant temperature

The room is sized 4.0 by 6.0 m (2.7 m high) with a south facing window sized 5.0 by 2.3 m and is ventilated with 2.0 air changes per hour between 8:00h and 20:00h and with 0.5 air changes per hour between 20:00h and 8:00h. The simulation was carried out for the months

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[1] The example is only used to illustrate the concept of data mining. Later examples will show how data mining can be used on more complex design configurations (section 5.5.15, 7.2.3).

of June, July and August using the kew67 climate data set. Figure 5.12 shows the performance predictions of the resultant temperature obtained from the simulation run. It can be seen that the room has (as might be expected) an overheating problem.

5.5.11 Association mining

The association mining function is only incorporated into the Intelligent Miner and not by the CART system. The following evaluation is therefore only based on the former tool.

Defining mining parameters

As described in 5.5.9, association mining discovers association rules that occur frequently together in a given set of data. As such, association mining has its roots in the so called “basket analysis”, where business tries to discover correlations between different articles the customers purchase (e.g. a customer who buys potatoes also buys fruit). This information can then be used in areas such as the development of marketing strategies.

As a result, association mining functions have been developed for categorical data sets. In consequence, the three input parameters, which were all continuous, had to be converted into categorical data. Direct solar radiation was grouped with a step length of 100 W/m^2 and temperature data was grouped with a step length of 2 °C.

Association mining results analysis

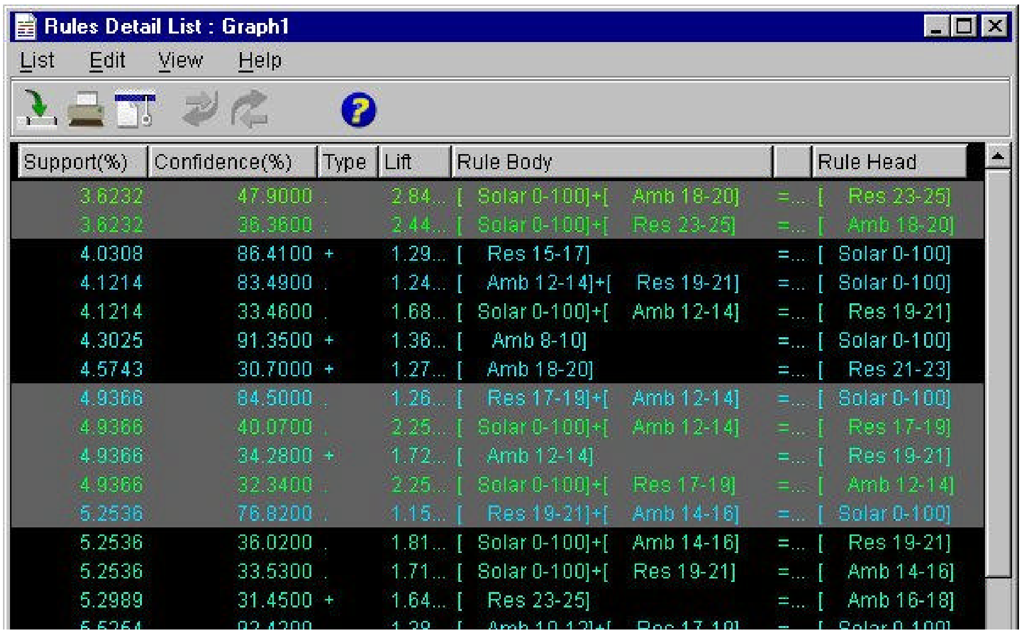
The analysis of an association mining session creates rules as described previously. Megiddo and Srikant [1998] describe the algorithms used by the Intelligent Miner to generate the rules. Figure 5.13 shows rules that were obtained from the mining session with the Intelligent Miner. Each rule comprises a rule body and a rule head. The first rule explains that if the solar radiation lies in between 0 and 100 W/m^2 and the ambient temperature is between 18 and 20 °C then the resultant temperature lies in the range 23 to 25 °C.

Other values obtained from the association mining analysis are support, confidence, type and lift values. All of these values are measures of the rule interestingness. The support value for a rule ‘A $\Rightarrow$ B’ is the percentage of instances where this pattern is present. In other words, the support of 3.6 for the first rule expresses that this rule can be related to 3.6 % of all occupied hours. The confidence value expresses how many of all the instances which contain the rule body also contain the rule head (how often did a solar radiation between 0 and 100 W/m^2 and an ambient temperature between 18 and 20 °C result in a resultant temperature between 23 and 25 °C). The lift expresses how far the actual confidence is exceeded by the confidence that would be expected if the rule body and rule head were statistically independent entities. The lift is determined as:

Lift (Rule) = Confidence (Rule) / Expected Confidence (Rule)

The confidence is specified as:

Confidence (Rule) = Support (Rule body n Rule head) / Support (rule head)



Rules Detail List : Graph1

List Edit View Help

Support(%)	Confidence(%)	Type	Lift	Rule Body		Rule Head
3.6232	47.9000	.	2.84...	[Solar 0-100]+[Amb 18-20]	=...	[Res 23-25]
3.6232	36.3600	.	2.44...	[Solar 0-100]+[Res 23-25]	=...	[Amb 18-20]
4.0308	86.4100	+	1.29...	[Res 15-17]	=...	[Solar 0-100]
4.1214	83.4900	.	1.24...	[Amb 12-14]+[Res 19-21]	=...	[Solar 0-100]
4.1214	33.4600	.	1.68...	[Solar 0-100]+[Amb 12-14]	=...	[Res 19-21]
4.3025	91.3500	+	1.36...	[Amb 8-10]	=...	[Solar 0-100]
4.5743	30.7000	+	1.27...	[Amb 18-20]	=...	[Res 21-23]
4.9366	84.5000	.	1.26...	[Res 17-19]+[Amb 12-14]	=...	[Solar 0-100]
4.9366	40.0700	.	2.25...	[Solar 0-100]+[Amb 12-14]	=...	[Res 17-19]
4.9366	34.2800	+	1.72...	[Amb 12-14]	=...	[Res 19-21]
4.9366	32.3400	.	2.25...	[Solar 0-100]+[Res 17-19]	=...	[Amb 12-14]
5.2536	76.8200	.	1.15...	[Res 19-21]+[Amb 14-16]	=...	[Solar 0-100]
5.2536	36.0200	.	1.81...	[Solar 0-100]+[Amb 14-16]	=...	[Res 19-21]
5.2536	33.5300	.	1.71...	[Solar 0-100]+[Res 19-21]	=...	[Amb 14-16]
5.2989	31.4500	+	1.64...	[Res 23-25]	=...	[Amb 16-18]

Figure 5.13: Rules obtained from the Association Mining session

If the rule body and rule head are statistically independent entities the percentage of instances that contain both rule head and rule body is equal to the product of the support for rule body and the support for the rule head:

Support (Rule body, rule head) = support (rule body) • support (rule head)

A correlation between the rule body and the rule head would result for this rule in a confidence that is higher than the expected confidence and hence generate a high lift value. The type expresses the influence of the rule body on the rule head, with '+' indicating a positive influence and '-' indicating a negative influence. It is again based on an analysis of the statistical dependency between rule head and rule body.

A first general observation when viewing the rules displayed in Figure 5.13 is the number of irrelevant rules that the association data mining session has produced. The second rule contains solar radiation and resultant temperature in the rule body and ambient temperature in the rule head. Although this is a pattern present in the data set it is not relevant information for the designer. These ‘useless’ rules are a result of the fact that association mining does not allow the definition of target or active variables. However, it is possible to rearrange the rules and only focus on the ones that have resultant temperature values in the rule head. This is shown in Figure 5.14.

It is now possible to view all the rules that are of interest. However, the analysis is not simple. Many different rules have to be viewed and an assessment needs to be carried out regarding their relevance, in combination with an evaluation of figures of statistical concepts the designers will probably not be familiar with. Another aspect is that every rule is an independent entity taken out of the entire ‘picture’, and a general understanding for the behaviour of a building is often the main aim when analysing performance predictions.

In response a tool named ‘Association Visualizer’ has been developed to display such information [IBM 1999 b]. Figure 5.15 gives an example. The dots represent different values for one or several data variables, and correlations between these entities are indicated with arrows pointing from the rule body to the rule head. Colour coding and thickness of the arrows indicates values about the interestingness of this rule.

Figure 5.14: Rules related to temperatures

The amount of information that can be obtained from this visualisation is however still limited, and most of it is again not of relevance. It is possible to reduce the information value to rules that contain resultant temperature in their rule head as shown in Figure 5.16. It can be seen that it is now easier to view the different rules in parallel, but the shift in terms of knowledge presentation in comparison to a conventional performance prediction analysis display still forms a barrier that reduces the applicability of association mining in the day-to-day building design process.

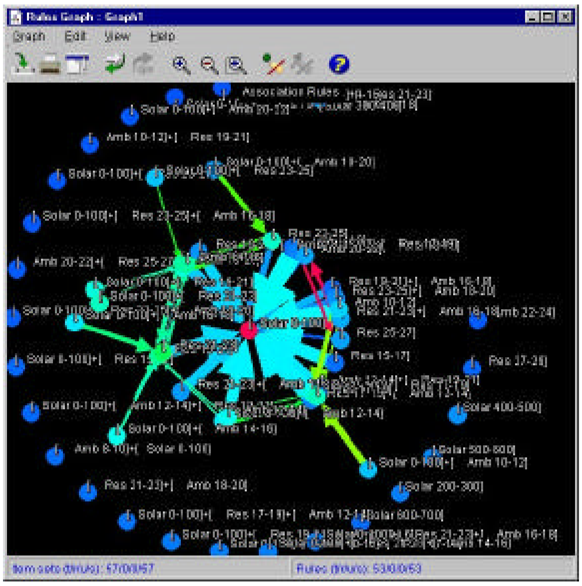


Figure 5.15: The Association Visualizer

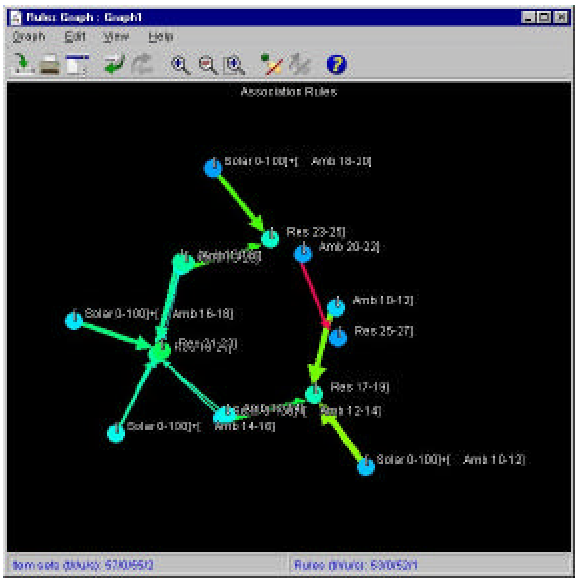


Figure 5.16: The Association Visualizer with reduced display

5.5.12 Clustering

As with association mining, clustering was again only incorporated with the Intelligent Miner. The following discussion is therefore based on this software tool.

Defining mining parameters

As described in 5.5.9, in a cluster analysis data is grouped with the aim of placing instances in segments in a way that maximises the similarity between instances of one segment and minimises the similarity between the instances of different segments. With this data mining technique it is possible to carry out an analysis with categorical and continuous data sets. The user can also specify so called active and supplementary variables. The active variables are used by the mining function when performing the clustering. The supplementary variables can be used to gain statistical information from the clusters that are found, determining the correlation between the cluster and supplementary variables.

The data mining session that is described in section 5.5.15 uses only the resultant temperature as an active parameter and the other variables that are included in the analysis (e.g. ambient temperature, air change rate) as supplementary variables. This enables the designer to obtain answers to typical design questions such as 'how does the ambient temperature and air change rate in a zone affect the resultant temperature in a zone?' because it ensures that the clusters are created only with respect to the resultant temperature. However, the correlation between resultant temperature and ambient temperature, air change rate, etc. is also determined (referring to association mining it could be stated that the user 'enforces' a certain variable, in this case resultant temperature, to act as the rule head). Otherwise the program might specify clusters where the variable of interest (resultant temperature) has a low priority, hence making the analysis of the results more difficult or impossible.

Clustering results analysis

Figure 5.17 depicts the results obtained from the clustering exercise that analysed the same result data set used in section 5.5.11 for the association mining analysis, but this time focused on periods with resultant temperatures above 27 °C (this produced the most interesting patterns in this particular analysis). Resultant temperature was specified as the active variable and ambient temperature and direct solar radiation as supplementary variables. Note that in the display supplementary variables are indicated with rectangle brackets around the variable name.

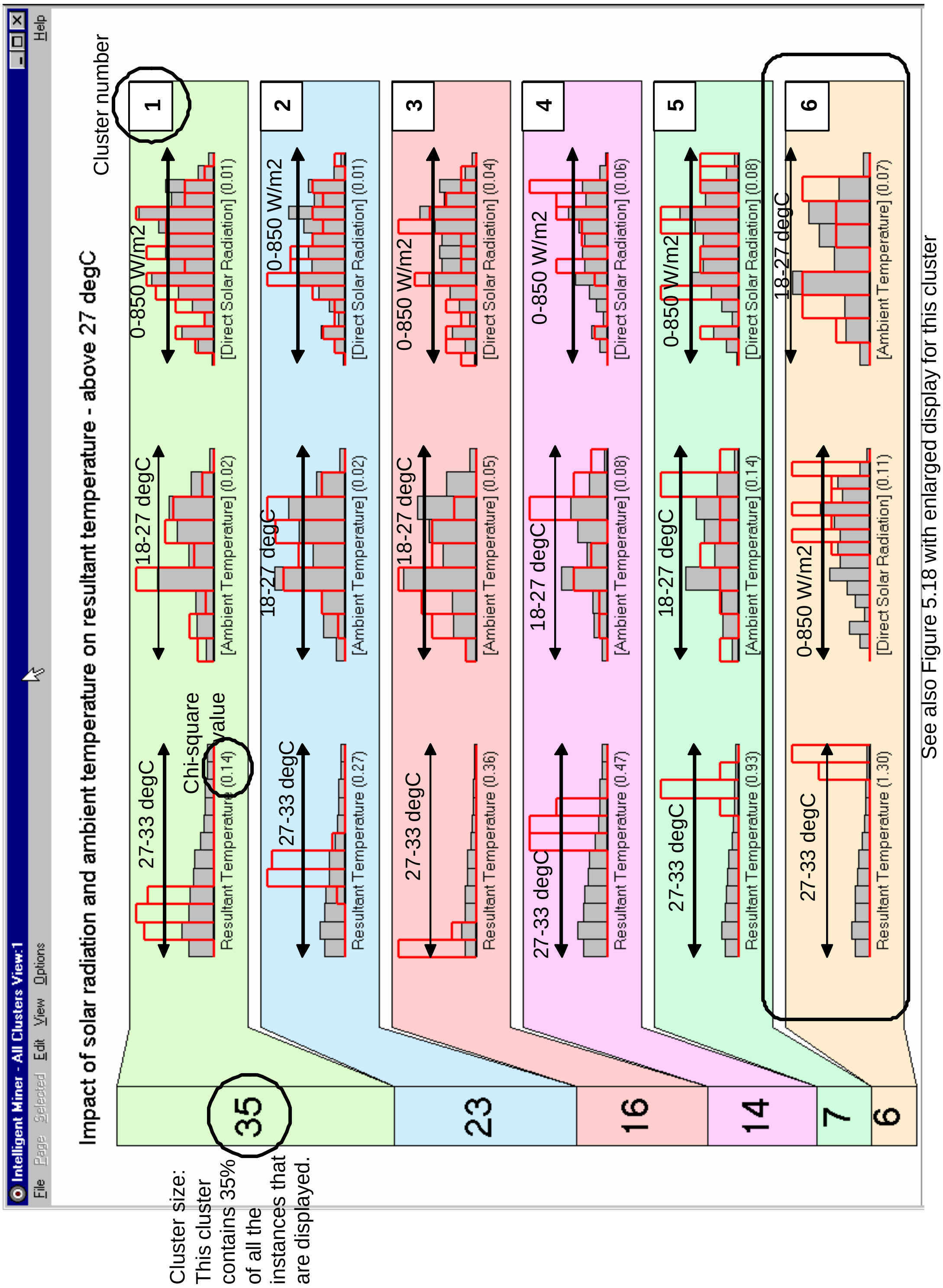


Figure 5.17: Result display for cluster analysis – all clusters are included

Instances with similar characteristics have been grouped into *clusters* ([Agrawal et al 1998] describe the algorithms on which the analysis is based). The display shows six rows, each representing one of the clusters. The software automatically determines a suitable number of clusters for a data mining exercise, but the user can overwrite this specification and define the number of clusters to be created. The numbers down the left represent the cluster size as a percentage; for example, the top cluster represents 35% of the data. The number on the right represents the cluster ID.

Figure 5.18: Result display for cluster analysis – only clusters 6

Each bar chart has two different displays. The solid bars represent the data for the entire data set and the red transparent bars represent the distribution of the instances that have been included into the particular cluster.

In addition to the clustering of the resultant temperature the program has also established for every variable in each cluster the chi-square (or goodness of fit) value. This value is determined by comparing the frequency distribution of the entire data set with the frequency distribution of instances that have been included in the cluster. If the difference is small the chi-square value is small, and vice versa. Normally the active variable will have high chi-square values because the clusters were defined using this variable. If a supplementary variable also has a high chi-square value this indicates for this particular cluster a potential correlation between the two variables (this issue will be discussed in more detail later in this section). The data mining program orders in its display variables for each cluster with respect to their chi-square value, with the variable with the highest chi-square value positioned on the left[1].

The interpretation can be illustrated with cluster 6 of the previous data mining exercise as depicted in Figure 5.18. From the analysis the designer can see that for this particular cluster, out of the two supplementary variables the direct solar radiation has the higher value, indicating a stronger correlation between high resultant temperature and direct solar radiation than between high resultant temperature and ambient temperature.

A general observation when viewing the entire results display is that the chi-squared values are higher for clusters with high resultant temperatures. This can be explained as follows: average temperatures can occur under a number of different conditions, but extreme temperatures require particular conditions, which will result in stronger correlations and higher chi-squared values.

A few more aspects are of importance when applying cluster analysis. One is the ordering of the variables with respect to their chi-square value. It was stated before that the chi-square value is determined by comparing the frequency of a variable when considering all the instances with the frequency of the instances that form the particular cluster (Figure 5.18 illustrated this concept). However, a high chi-square value does not necessarily indicate a positive correlation, as the following example shows. Figure 5.19 shows an imaginary result display from a cluster analysis. The top graph displays the target variable – the resultant temperature within a space in the building. The two lower graphs display the ambient temperature as a supplementary variable. In both cases the ambient temperature will

[1] This will normally be the active variable, but in exceptional cases it can also be a supplementary variable.

have a high chi-square value because the frequency distribution of the ambient temperature in the entire data set is different from the frequency distribution of the ambient temperature values that occur in the clusters. However, a positive correlation exists only in the first case between the high resultant and high ambient temperature. In the second case a high resultant temperature occurs at times of low ambient temperatures, hence there is no correlation between high internal and ambient temperatures.

5.5.13 Tree classification mining

Tree classification mining is the third data mining technique that was analysed as part of this study. Both the CART system and the Intelligent Miner offer this functionality, but the CART system presents the results more comprehensively and extensively than the Intelligent Miner. In consequence the following presents only results from the CART system. [Salford Systems 2002 a] describe the principles on which the analysis of the CART system is based; Shafter et al [1996] and Mehta et al [1996] describe them for the Intelligent Miner.

Defining mining parameters

As described in 5.5.9, tree classification analysis intends to find rules from the dataset it investigates with a focus on one particular variable. A tree classification differs hence from cluster or association mining analysis because in this mining technique the user *has* to specify a target variable – the data mining tool will then determine the influence of the other variables on the target variable. The following section illustrates this issue.

Classification results analysis

Figure 5.20 shows the outcome from an analysis of the same data set in the form of a decision tree. A decision tree is a flow-chart-like tree structure, where each internal node (here displayed in green) denotes a test on a variable (e.g. ambient temperature), each branch represents an outcome of the test, and leaf nodes (displayed in red) represent classes, which contain values of the target variable (e.g. internal temperature). The top-most node in a tree is called the root node. By following down a path from the root node to the leaf node it is possible to derive the rule for a particular leaf node.

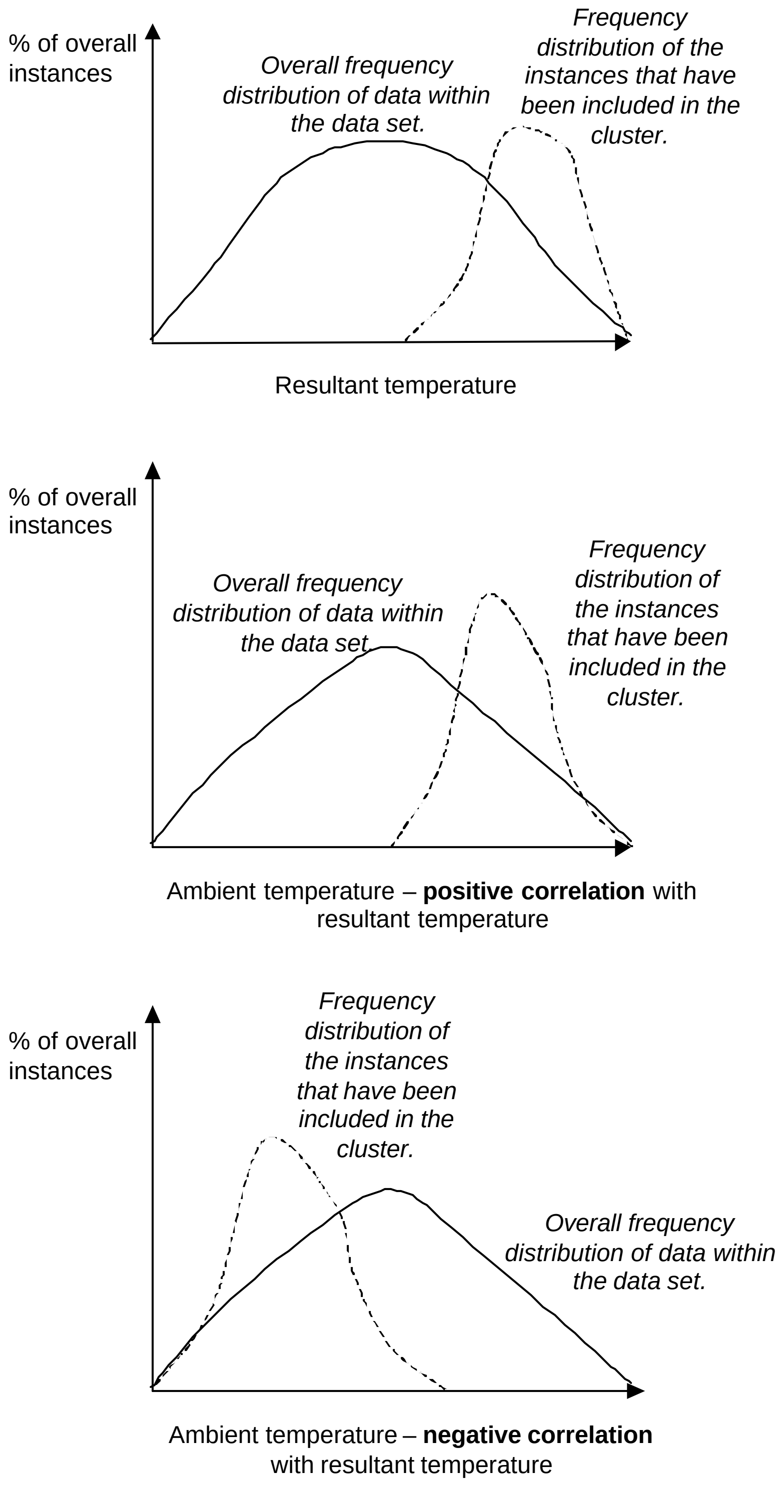


Figure 5.19: High chi-square values with negative and positive correlation

In this example, the resultant temperature has been set as the target variable. Independent variables are ambient temperature and solar radiation. The top node has a value of 19.975 °C ambient temperature. This means that all instances where the ambient temperature is below this value are related to one branch; the other instances will be allocated to the second branch. Each branch is then split into sub-branches, until the terminal or leaf node is reached. Continuous variables can be tested at different tree levels (e.g. temperature <19 °C, <17 °C, >13 °C). Categorical variables can only be tested once.

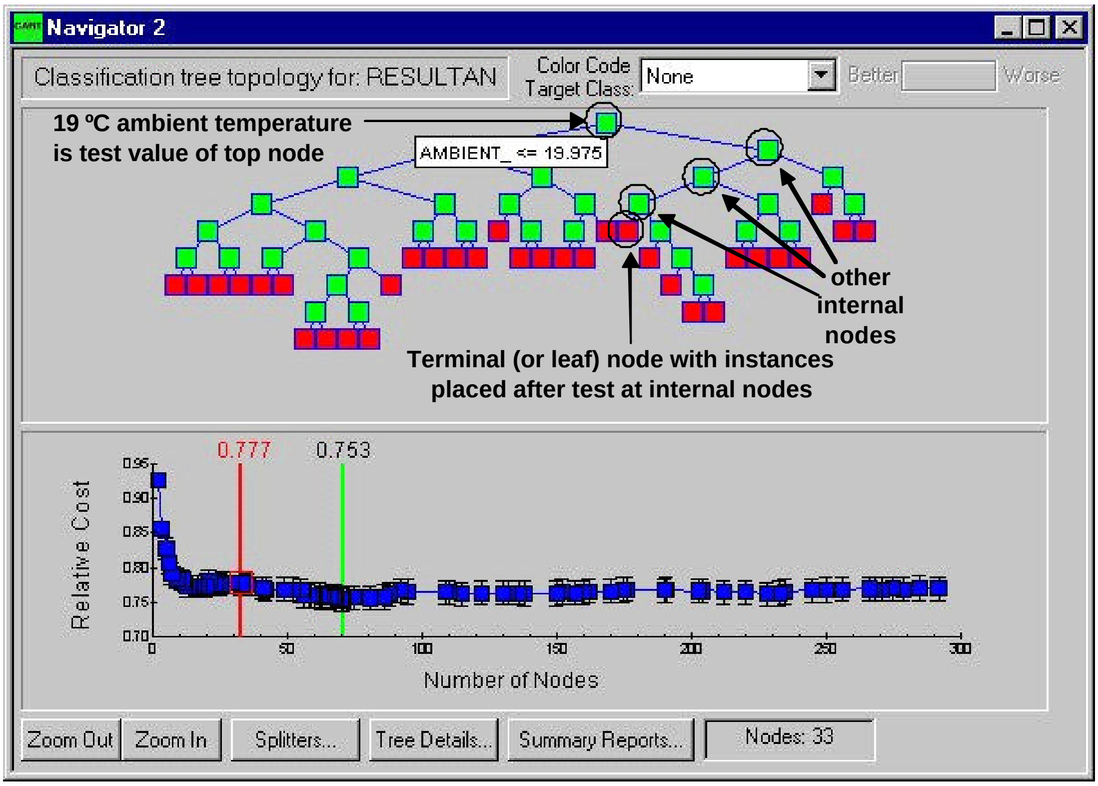


Figure 5.20: Result output from a classification analysis

Trees can grow very large so that it can become necessary to reduce their size when carrying out an analysis – the so-called pruning of the tree. Here two different types can be distinguished: post-pruning (sometimes also called backward pruning) where the user prunes after the mining session, and pre-pruning (or forward pruning) where the user defines from the start that the tree shall not exceed a certain size. The pruning type applied can influence the outcome of the analysis [Witten and Frank 2000]. The graph at the bottom of Figure 5.20 indicates how far the information value of the tree is affected by post-pruning (lower values indicate higher information value).

Different information can be obtained from the tree classification analysis. By viewing for the tree structure the variables associated to each node (splitters) it is possible to get an understanding of how variables contribute to patterns that were found in the data (see Figure 5.21).

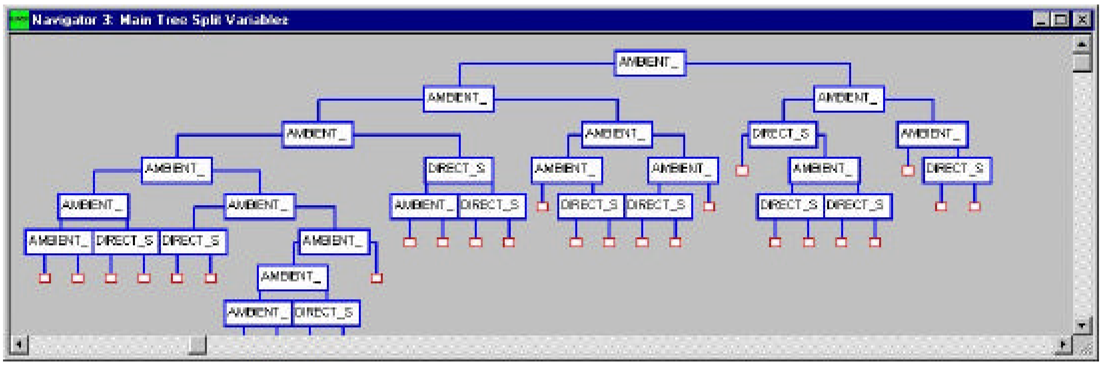


Figure 5.21: Splitters of the tree diagram

In many cases the user of the program will be interested in the distribution of the different values of the target variable in the different leaf nodes, such as, for example, in which leaf nodes high resultant temperatures occur. This information in combination with the splitter variables (and the value of the different splitter variables) can support the designer in understanding which parameters caused the high resultant temperature.

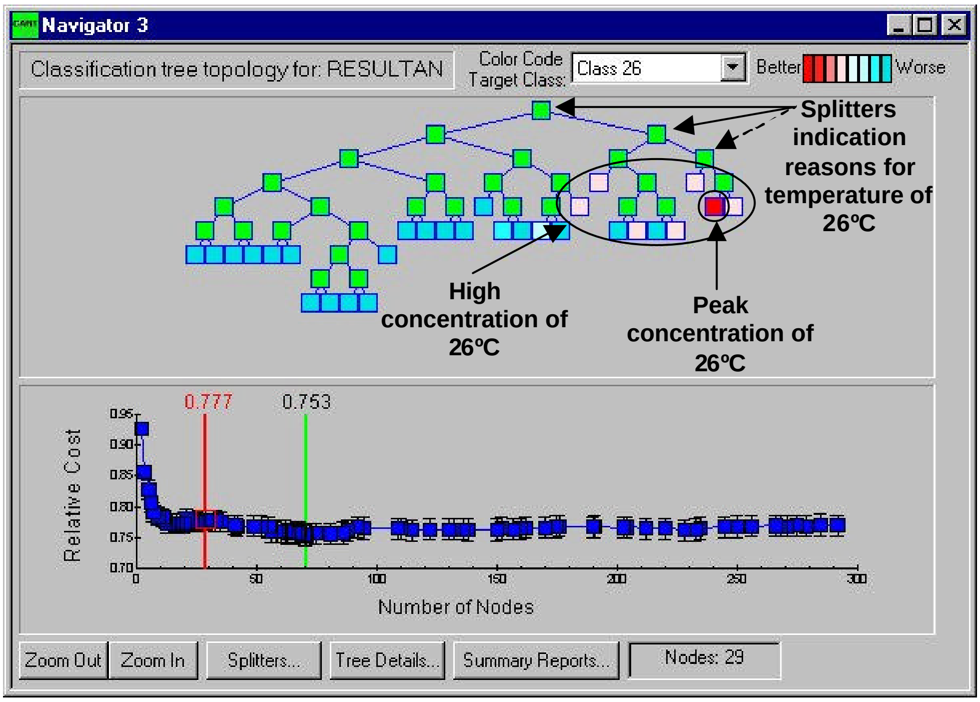


Figure 5.22: Colour code indicating concentration of 26ºC resultant temperature in terminal nodes

To enhance the extraction of this information CART displays a colour code that indicates appearances of target variable values in terminal nodes (See Figure 5.22). A red colour indicates that a value is often represented in a leaf node. In the example the target class is 26 (resultant temperature of 26ºC), which occurs in leaf nodes on the right hand side of the tree, with the biggest concentration at the second node from the right.

5.5.14 Discussion of different data mining techniques

Task	Association Mining	Clustering	Tree classification
Understanding of general behaviour of building	- -	+	-
Potential of control of mining focus by defining target variable	0	+	+
Visual display of results	- -	+	0

Table 5.8: Rating of data mining techniques
(++ very easy/good, + easy/good, 0 neutral, - difficult/limited, -- very difficult/limited)

Table 5.8 rates different aspects of data mining related to the analysis of performance predictions obtained by building simulation. It indicates that the results display of a cluster analysis visualises comprehensively patterns in the overall data in a display format familiar to the designer. By analysing the different clusters the designer can see how target variable values within the cluster range are affected by supplementary variables. This analysis is carried out for each cluster independently; this increases the information value in comparison to tree classification, which analyses for all the instances of the data set.

Tree classification has, in comparison to association mining, the advantage that it allows the definition of a mining focus by defining an active or target variable. However, the analysis of the mining results is rather tedious, with the instances split into a large variety of different terminal nodes. The visual display is generally more removed from display normally used in the design process, which is a barrier for its application by building designers. It makes the extraction of knowledge less straightforward than is the case with clustering.

Association mining has a number of disadvantages: it produces a large number of redundant rules and has a poor visual display of the information obtained from the mining analysis.

In consequence it was concluded that clustering is most suitably for the analysis of data sets obtained from a simulation exercise and was hence the only technique applied in following case study which shows with more complex example how data mining can be applied by building designers. Another example is given in a case study in chapter 7.

5.5.15 Case study

The case study evaluates the office building displayed in Figure 5.23. The building incorporates a fully glazed reception area (indicated in red on the right hand side of the building) and a fully glazed breakout zone (the long narrow blue section indicated at the top of the building).

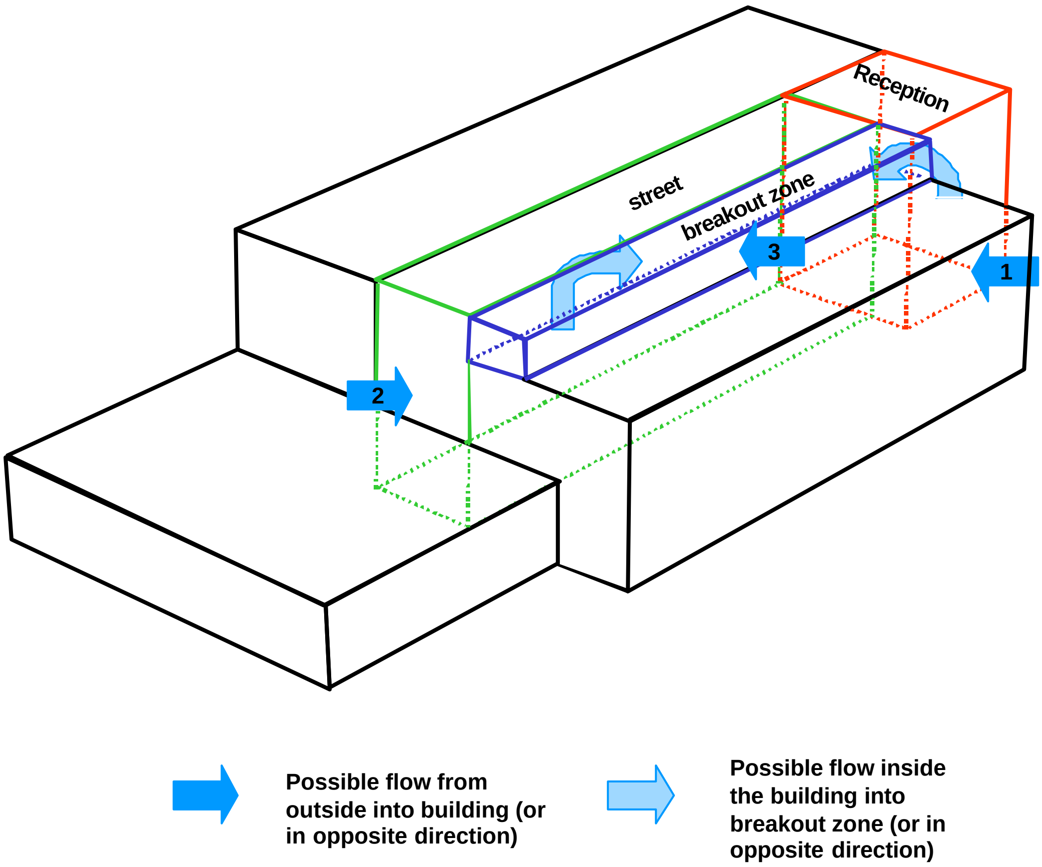


Figure 5.23: The model with reception, breakout zone and street

The building is naturally ventilated with three external ventilation openings: one at the reception (see number 1 in Figure 5.23); one at the circulation area called street (number 2 in Figure 5.23, the street is also indicated in green) and one at the breakout zone (number 3).

There are also internal air flow paths from the reception into the breakout zone and from the street into the breakout zone. Both internal air flow paths are indicated in Figure 5.23 as green arrows. The following analyses were carried out:

1. A comfort analysis in the breakout zone in summer.
2. A comfort analysis in reception in winter.

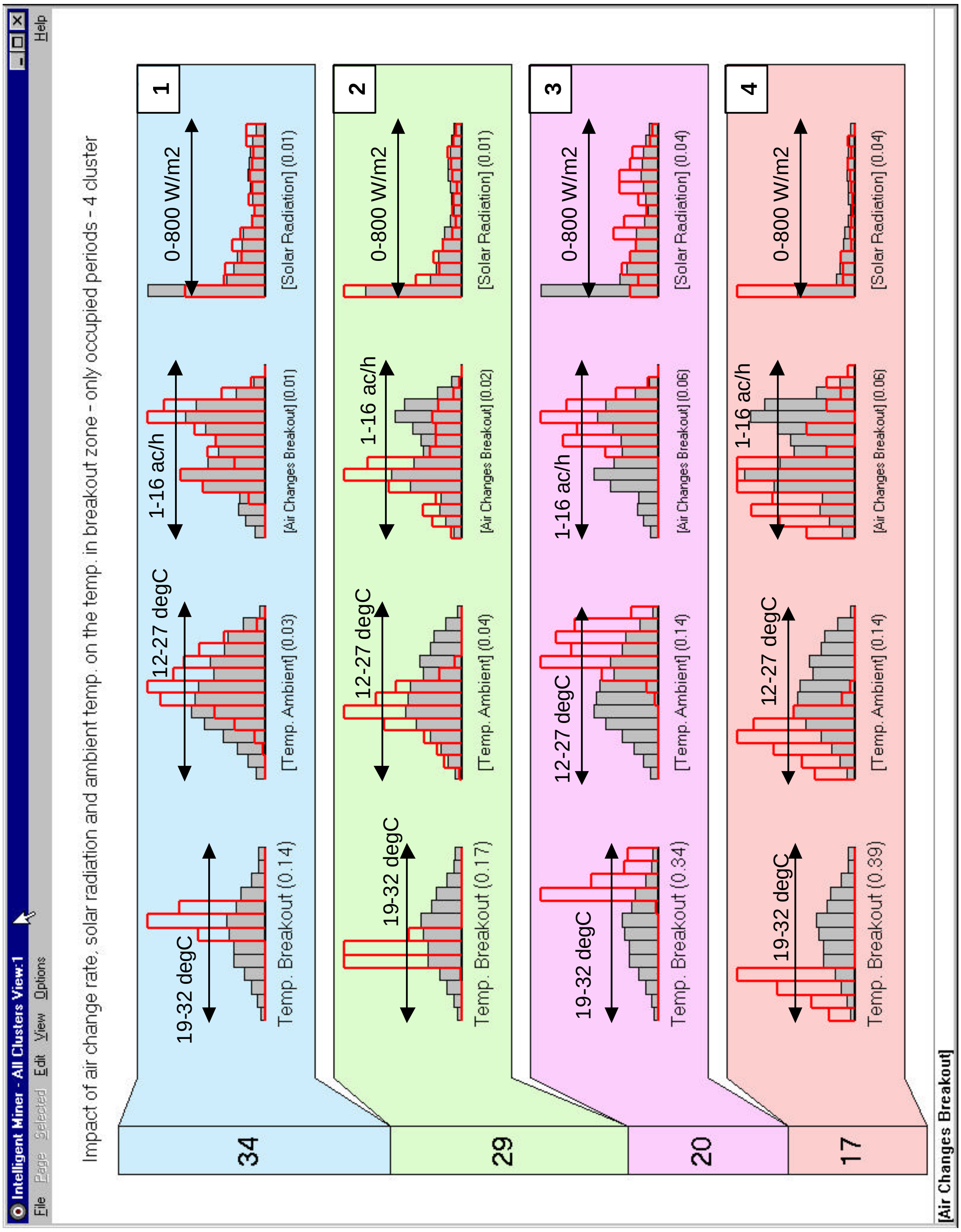


Figure 5.24: Result display for cluster analysis (summer resultant temperature in breakout zone) – all clusters

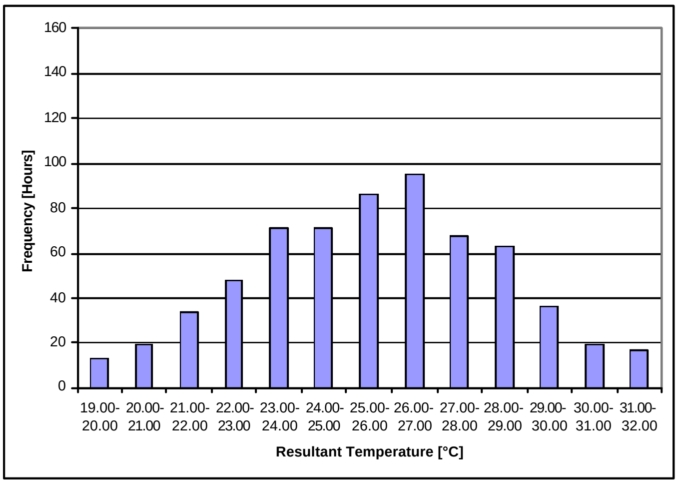
Figure 5.24 show the results of the cluster data mining exercise for the summer case. The building was simulated for a three-month period (June, July and August) and the analysis focused only on occupied periods. The resultant temperature in the breakout zone was specified as the active variable and the ambient temperature, air change rate in the breakout zone and solar radiation as supplementary variables.

It can be seen that the breakout zone suffers from a significant overheating problem (see in Figure 5.24 frequency binning of variable 'Temp. Breakout' for whole data set). Another general observation is that the correlation between ambient temperature and internal resultant temperature is strongest and weakest for the air change rate and solar radiation respectively. This indicated that radiation entering the space unlikely to be the reason for the high temperatures in the space. This was also confirmed by an additional simulation of the hypothetical case that the breakout zone has no windows and hence the space did not receive any solar gains at all (see Figure 5.25). Although the resultant temperature dropped significantly (due to the replacement of glass with opaque construction for the entire façade and roof of the space) the air temperature still rose up to 32 °C, and this despite the fact that the potential of the room as a heat sink had increased greatly with the change of construction.

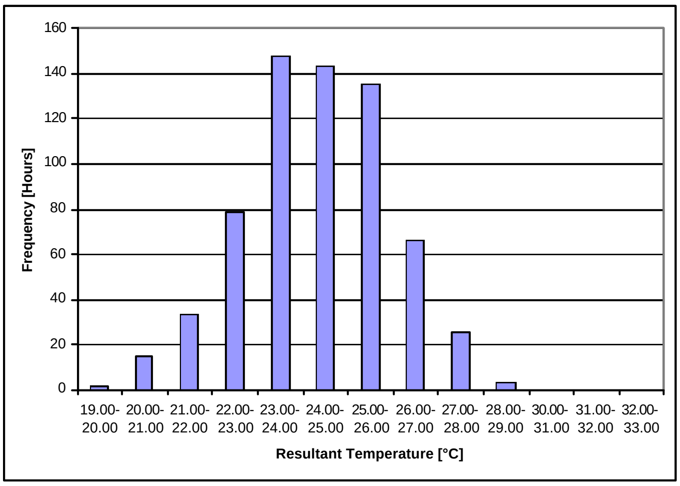
Viewing the energy flows in the building by a causal analysis as described in 5.2.1 could also have provided the information that was obtained from the data mining study (e.g. by focusing on one hour when high internal temperatures occurred). However, data mining includes all hours when a problem occurred during the analysis. This can be important for situations where boundary conditions are frequently fluctuating (as in this case study where air flow rate through the breakout zone was highly variable). If the user had selected one particular time simulation time step for the investigation the conclusion might not have been representative for the common behaviour of the building.

Figure 5.26 shows the results that were obtained for the winter assessment. It can be seen in cluster 3 (cluster with resultant temperatures close to 16 °C) that the chi-square value of the ambient temperature is higher than for the infiltration rate. This indicates that low resultant temperatures in the ground level of the reception area are more a function of low ambient temperatures and not so much of infiltration rates.

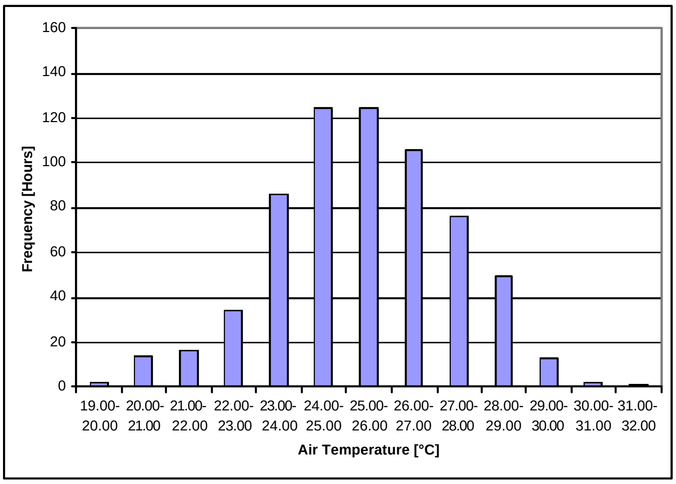
Another observation is that temperatures close to 16 °C occur mainly in the morning and evening (see graph "time of time"). In this case it may, for example, be possible to conclude that the poor temperature conditions are not too relevant because in this period this section of the building will only be sparsely occupied.



(a)



(b)



(c)

Figure 5.25: Temperatures breakout zone: (a) resultant temperature with windows (b) resultant temperature with no windows (c) air temperature with no windows

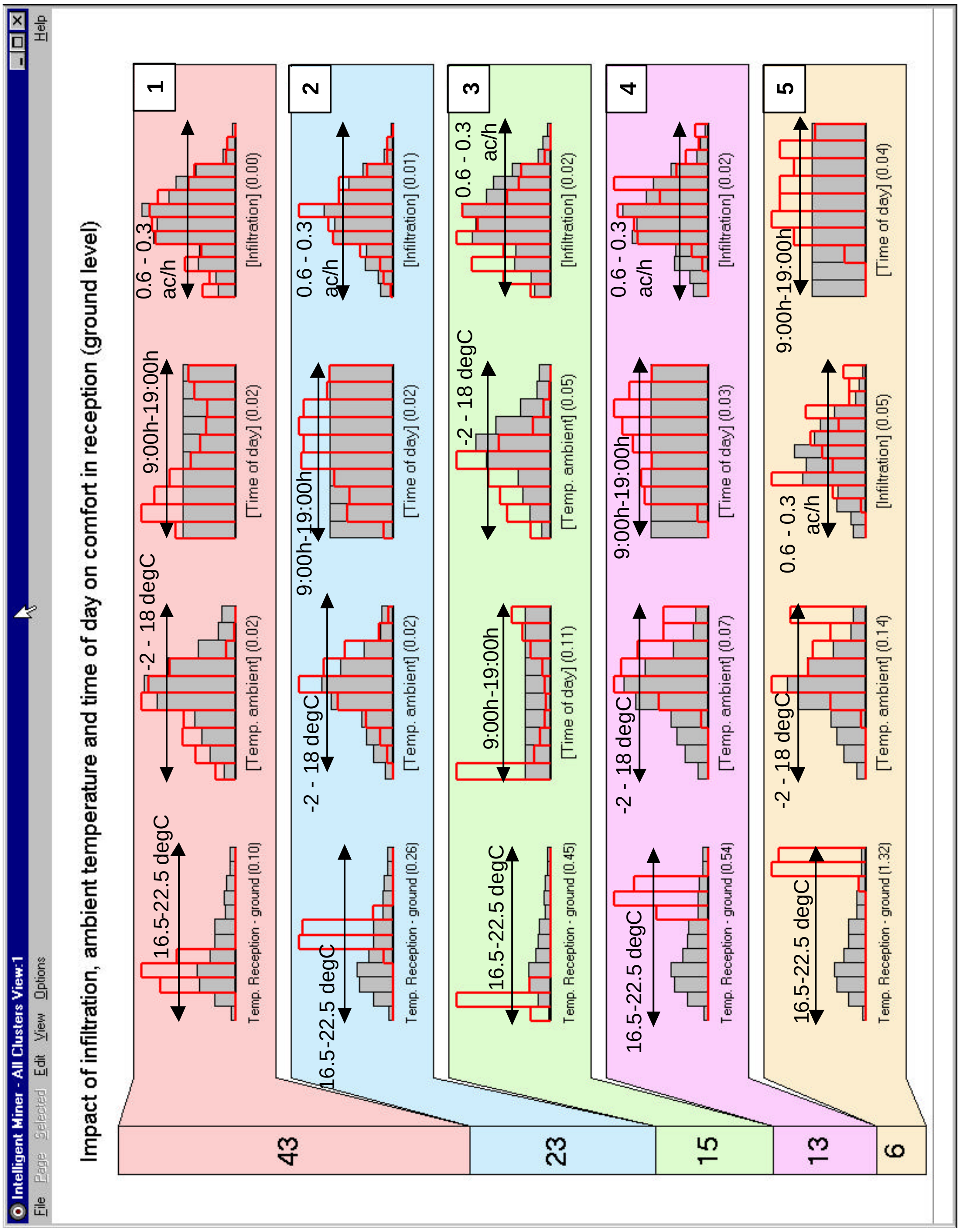


Figure 5.26: Result display for cluster analysis (winter resultant temperature in reception) – all clusters are included

The variables that where chosen for the winter assessment differ from to the ones selected for the summer assessment (no solar radiation but time of day). Generally there is no rule which variables to select, but the designer can specify variables that shall be included in the analysis. In consequence the focus might change (omitting some variables, inclusion of others) after some initial mining runs. This issue will be discussed in more detail in the next section).

5.5.16 General discussion of the use of data mining in conjunction with simulation

The previous examples have shown how cluster analysis, as one data mining technique, can enhance the analysis of performance predictions obtained from a simulation exercise. This section discusses general aspects related to the use of data mining in conjunction with simulation.

What defines a data mining task?

A popular misconception about data mining is to expect the data mining system to automatically dig out all the valuable knowledge that is embedded in a large dataset. Although it may at sound at first appealing to have such an autonomous data mining system, in practice, such a system would uncover an overwhelmingly large set of patterns, and most of the patterns discovered in the analysis would be irrelevant for the user (as seen in the case of association mining). A more realistic scenario is to communicate with the data mining system, using additional questions to examine the findings and direct the mining process (after [Han and Kamber 2001]):

- What is task relevant data?
- What kind of knowledge do I want to mine?
- What background knowledge could be useful?
- How do I want the discovered patterns to be presented?

This approach follows the philosophy of the design assisting DDSS described earlier in this chapter (section 5.2.2). In consequence it is actually not guaranteed that the first analysis will provide the required information– the user might have defined a mining exercise that does not reveal important patterns. In that case the analysis needs to be refined. The creation of different mining exercises is supported by avery flexible definition of a mining task. The user can quickly change variables to be included in a mining run, in combination with filters that can be defined for all the variables (e.g. only focus on times with a resultant temperature above 27 °C, occupied periods, times of high occupancy densities, etc.).

Validity of identified patterns

Different approaches have been developed with regard to how information that was obtained from a data mining session can be tested with respect to its general validity. Witten and Frank [2000] devote an entire chapter of their book to this issue, including techniques such as training and testing, cross-validation and comparison of results obtained from different data mining techniques. However, these strategies make the data mining process much more complex. Also, when applying data mining in conjunction with building simulation, it is possible to immediately test what has been learned by creating a design variation and then assesses whether or not a design change leads to a performance improvement.

Some data mining tools, e.g. the CART system, automatically test the value of the information that has been obtained from the data mining run. If this information is found to be insignificant it is not presented to the user – the data mining session will not build a tree.

Data transfer between simulation and data mining software

Data transfer is currently the main barrier for the application of data mining in conjunction with building simulation. For routine use, it is necessary to develop filters that export the data in the native form of the data mining tool (see Figure 5.27). However, because the development of data mining programs is at an early stage no general format has been defined for input data - the three data mining programs evaluated had three different data import formats. In addition should simulation tools export data items that could be of interest for a data mining exercise such as whether a particular zone is occupied at the different simulation time steps. Only when during a data mining session all variables that are potentially of relevance are available to the designer the tool can be utilised to its full potential.

Simulation period

The usefulness of data mining depends to a large extent on the type of analysis carried out. If the aim of the simulation is to predict the building performance for a typical seasonal day or an extreme week, the data mining might not contribute additional information. If, however, the scope is to assess the building performance over a longer period (e.g. from spring to autumn), data mining becomes considerably more useful. With data mining it is possible to take the analysis one step further: a design could be simulated with different climate sets, emulating extreme conditions (e.g. very hot summer) which will occur only rarely, but which will nevertheless affect the performance of the building.

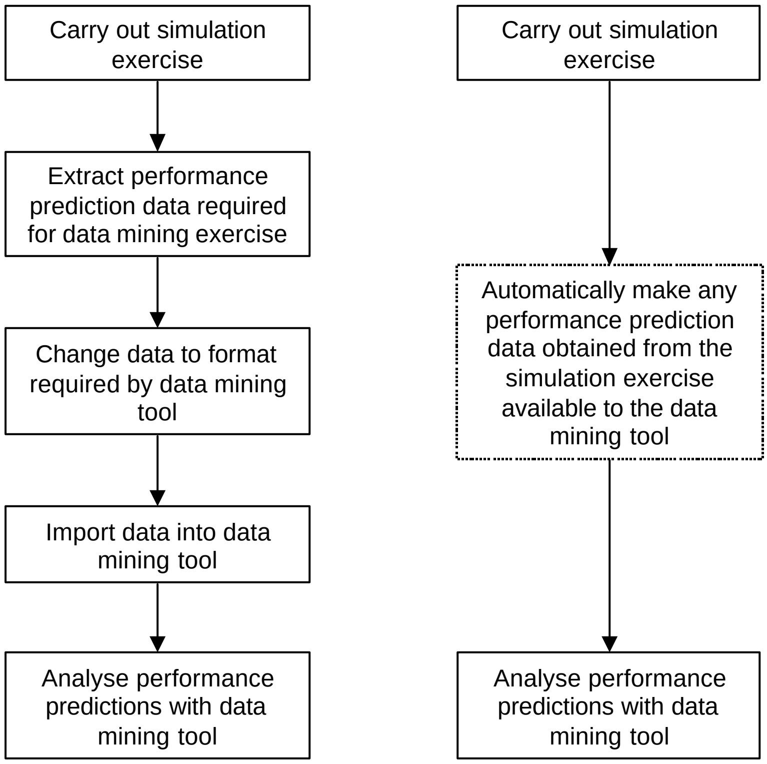


Figure 5.27: Data transfer between simulation and data mining software: Currently and ideally

Where will data mining go from here?

The data mining community currently holds the view that data mining is moving "from an early adopter to an early majority application" (see [Agrawal 1999] or [Han and Kamber 2001] as an example). If this is the case then it can be envisaged that resources will be available for additional developments in the area of data mining. Some will not be of relevance for use in conjunction with building simulation, such as speeding up the data mining process of large data sets by parallel mining using different machines [Agrawal et al 1993]. However, other developments will be beneficial: examples are improved data exchange, better visual display and an enhancement of the assessment of what has been learned.

5.6 Closing remarks

This chapter first dealt with different types of performance prediction analysis undertaken at each design stage and concepts how knowledge could be extracted from simulation result data sets. The latter included a discussion of causal analysis and design guidance analysis. The discussion of design guidance analysis also contained a comparison of two different philosophies behind DDSS: The design assistant and the design automation approach. The application of the design assistant approach was favoured because the designer gains insight into reasons for the predicted building performance.

Findings from this initial research influenced work described in the second part of the chapter: research into tools and techniques to enable designers to retrieve knowledge from simulation result data sets along with discussions how to present it to the designer. It had resulted in the development of an expanded IPV and the introduction of data mining as a novel approach to analyse these data sets.

The expanded IPV was developed for the Outline Design Stage and is tailored towards the requirements of this design stage. It contains benchmark figures, whole building energy consumption figures and detailed explanation of the performance predictions, which can be applied in combination with an energy flow analysis. The research had identified this as important to enable non-simulation experts to understand the performance predictions.

The reason for research into the application of data mining is considered justified by the fact that the generation of large datasets with simulation requires data analysis with appropriate tools. Different data mining techniques were described, out of which three (association mining, clustering and classification mining) were selected for tests in conjunction with simulation. It was concluded that clustering had the best applicability in the building design process as it has the most comprehensive visual display, which is also in a format that the designer is familiar with. In addition, it indicated correlations between target and supplementary variables, independent for each cluster. A general discussion of the applicability of data mining in the design process and in conjunction with simulation concluded that data mining follows the design assistant approach where the designer has control over the evaluation process and decision making.

Having so far presented tools, structures and techniques for the integration of simulation into the design process, the next two chapters discuss and illustrate their combined application within the building design process and also address implementation issues. The later is another consideration that needs to be addressed as part of the application of simulation within the building design process.

References

Agrawal R, "Data Mining: Crossing the Chasm", Invited Talk at the 5th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD-99), San Diego, California, August 1999.

Agrawal R, Arning A, Bullinger T, Mehta M, Shafer J, Srikant R, "The Quest Data Mining System", Proceedings of the 2nd International Conference on Knowledge Discovery in Databases and Data Mining, Portland, Oregon, 1996.

Agrawal R, Gehrke J, Gunopulos D, Raghavan P, "Automatic Subspace Clustering of High Dimensional Data for Data Mining Applications", Proc. of the ACM SIGMOD International Conference on Management of Data, Seattle, Washington, 1998.

Agrawal R, Imielinski T, Swani A N, "Database Mining: A Performance Perspective", IEEE Transactions on Knowledge and Data Engineering, Volume 5, Number 6, 1993.

Ashford C, "Data Mining – a Tool for System Commissioning", Presentation at the Energy Show 98, Dublin, 1998.

ASHRAE, "Building System Design and Synthesis and Optimisation", Invitation for the Submission of a Research Proposal on an ASHRAE Research Project, 1998.

Badger C, Project Director at HLM Design, Personal Communication, 2002.

BRECSU and Oscar Faber, "BRECSU 77/98", Software for the Evaluation of Alternative Cooling Systems.

Cabena P, "Discovering Data Mining: from Concept to Implementation", Prentice Hall, 1998.

CIBSE (Chartered Institution of Building Services Engineers), "Energy Demands for Air Conditioned Buildings", CIBSE publication, 1997.

Clarke A, "Energy Simulation in Building Design", Butterworth-Heinemann, Oxford, 2001;

Crawley D, Personal Communication, 2002.

De Groot, E H, Pernot C E E, "Energy Impact Knowledge-Based Systems Project: Outcomes of the Netherlands Workshop", Proceedings of the 4th Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, Eindhoven (CD format), 1998.

Doggart J, "How green is my office? The Office Toolkit", The Architect's Journal, pp 44-45, August 1995.

Donaldson I, Mc Callum K, "The Role of Computational Prototypes in Conceptual Models for Engineering Design", Chapter in the Book "Artificial Intelligence in Design" '94", published by Kluwer Academic Publishers, pp 3-20, 1994.

Donn M R, "A Survey of Users of Thermal Simulation Programs", pp 65-72, Proceedings Building Simulation 97, Prague, pp 65-72, 1997.

DTLR a (Department of Transport, Local Government, Regions), "The Building Regulations 2000, Part L1", 2002.

DTLR b (Department of Transport, Local Government, Regions), "The Building Regulations 2000, Part L2", 2002.

Duffy S, Duffy A, "Sharing the Learning Activity Using Intelligent CAD", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Volume 10, pp 83-100, 1996.

EEBPP (Energy Efficiency Best Practice Programme), "Homepage of the UK Government's Energy Efficiency Program for the Built Environment", http://www.energy-efficiency.gov.uk/, 2002.

ESRU, "ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series", University of Strathclyde, Glasgow, 2002.

Field J, Soper J, Jones P, Bordass W, Grigg P, "Energy Performance of Occupied Non-domestic Buildings: Assessment by Analysing End-use Energy Consumptions", Building Services Engineering Research and Technology, Vol. 18, No. 1, CIBSE, pp 39-46, 1997.

Gero J S, D'Cruz, Radford A D, "Energy in Context: A Multicriteria Model for Building Design", Building and Environment, Volume 18, No 3, pp 99-107, 1983.

Han J, Kamber M, "Data Mining – Concepts and Techniques", Morgan Kaufmann Publishers, 2001.

Ho C, Director of Consultancy Company "Building Simulation" Personal Communication, 1999.

IBM a, "Using the Association Visualizer", Version 6 Release 1, IBM, 1999.

IBM b, "Using the Intelligent Miner for Data", Version 6 Release 1, IBM, 1999.

IBM, "IBM Data Management Scholars Program Homepage", http://www-3.ibm.com/software/data/highered/, 2002.

Janak M, Personal Communication, 2002.

Jones P b, "Energy in Buildings", Workshop organised by the Chartered Institution of Building Services Engineers (CIBSE), Manchester, 2001.

Klemm, K, Marks W, Klemm A, "Multicriteria Optimisation of the Building Arrangement with Application of Numerical Simulation", Building and Environment, Volume 35, 2000.

LBNL a (Lawrence Berkeley National Laboratory), "Building Design Advisor Homepage", http://kmp.lbl.gov/BDA, 2002.

LBNL b (Lawrence Berkeley National Laboratory), ”GenOpt Homepage”, http://gundog.lbl.gov/GO/index.html, 2002.

Lionheart Publishing, “Statistical Analysis Software Survey”, http://www.lionhrtpub.com/orms/surveys/sa/sa8.html, 2001 (viewed 2002).

Littell R C, “Computing Resources Webpage”, http://sta6166.ifas.ufl.edu, 2002.

Macdonald I A, ‘Quantifying the Effects of Uncertainty in Building Simulation”, PhD Thesis University of Strathclyde 2002.

Mahdavi A, Akin O, Zhang Y, “Formalization of Concurrent Performance Requirements in Building Composition, Proceedings of the 4h Conference on Design and Decision Support Systems in Architecture and Urban Planning”, 1998.

Malkawi A, “Representing collaborative Multi-knowledge Agents as Generic Rules”, Proceedings of the 4th Conference on Design and Decision Support Systems in Architecture and Urban Planning, Maastricht, The Netherlands, 1998.

Marks W, “Multicriteria Optimisation of Shape of Energy-Saving Building”, Building and Environment, Volume 32, pp 331-339, 1997.

MathWorks, “MathWorks homepage (MathWorks have also Created the MATLAB software system)”, http://www.mathworks.com/, 2002.

Megiddo N, Srikant R, “Discovering predictive association rules”, Proceedings of the 4h International Conference on Knowledge Discovery in Databases and Data Mining, New York, USA, 1998.

Mehta M, Agrawal R, Rissanen J: "SLIQ: A Fast Scalable Classifier for Data Mining", Proc. of the Fifth International Conference on Extending Database Technology, Avignon, France, 1996.

Minter R, Gale A, “A Systems Approach to Sustainability: Advice to the Countryside Commission”, Published by the Institute of Policy Analysis and Development, 1993.

NREL (National Renewable Energy Laboratory), ”Energy 10 Homepage”, http://www.nrel.gov/buildings/energy10, 2002.

Pohl J, Chapman A, Pohl K J “Computer-aided Design in the 21st Century: some Design Guidelines”, Proceedings of the 5th International Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, Eindhoven, pp 307-324, 2000.

Salford Systems a, “Salford Systems White Paper Series”, http://www.salford-systems.com/whitepaper.html, 2002.

Salford Systems b, “The Salford Systems and CART Homepage”, http://www.salford-systems.com/, 2002.

Salford Systems, “Cart for Windows User’s Guide”, Salford System, 2000.

Sariyildiz S, Ciftcioglu O, van de Veer, “Information Ordering for Decision Support in Buildings”, Proceedings of the 4th International Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, Eindhoven (CD format), 1998.

Schneider A, “Solararchitektur für Europa”, Birkhäuser Verlag, 1996.

Shafter J C, Agrawal R, Mehta M: "SPRINT: A Scalable Parallel Classifier for Data Mining", Proc. of the 22th International Conference on Very Large Databases, Mumbai (Bombay), India, 1996.

Simoff S, and Maher M L, “Ontology-based Multimedia Data Mining for Design Information Retrieval”, Proceedings of ACSE Computing Congress, Cambridge, 1998.

Smith G, Maher M L, “Data Mining Agents in a Virtual World”, Discussion Paper Published by the Key Centre of Design Computing and Cognition at the University of Sydney, 2001.

SPSS, “SPSS homepage”, www.spss.com, 2002.

Swain J L, “Looking for Meaning in an Uncertain World – 2001 Survey of Statistical Analysis Software Products”, http://www.lionhrtpub.com/orms/orms-10-01/survey.html, 2001 (viewed 2002).

Thomas L, Krebs C J, “A REVIEW OF Statistical Power Analysis Software”, http://www.zoology.ubc.ca/~krebs/power.html, 1997 (viewed 2002).

University of Waikato, “Weka Homepage”, http://www.cs.waikato.ac.nz/~ml/weka/, 2002.

Waterloo Maple, “Waterloo Maple Homepage (Waterloo Maple have also Created the Maple Software System)”, http://www.maplesoft.com, 2002.

Wetter M, “Design Optimisation with GenOpt”, Building Energy Simulation User News, Volume 21, pp 19-28, 2000.

Witten I H, Frank E, “Data Mining – Practical Machine Learning Tools and Techniques with Java Implementations”, Morgan Kaufmann Publishers, p 37, 2000.

CHAPTER 6

PRACTICAL IMPLEMETATION OF SIMULATION

6.1. Introduction

The three previous chapters described first a procedure developed to enable the effective use of simulation throughout the building design process (SSDP), followed by the description of an interface created specifically for the Outline Design Stage (ODS-Interface) and a discussion of performance prediction analysis and communication at different design stages.

The first part of this chapter shows how research contributions made in the previous chapters support the movement towards the use of simulation throughout and as an integral part of the building design process. The second part of this chapter puts the emphasis on practical implementation issues. It covers aspects such as model creation, quality assurance (QA), model documentation, management procedures, training and also discusses liability for performance predictions.

6.2 Use of simulation throughout the building design process

Figure 6.1 shows how research contributions described in previous chapters can be used to provide the integral application of building simulation throughout the building design process. The figure describes the process in principle; it is illustrated with a case study in the next chapter. From the figure it can be seen that while the main part of the research focused on the Detailed Design Stage and particularly the Outline Design Stage, some contributions to use simulation in the Scheme Design Stage have also been made. The general importance of making contributions to support the use of simulation at the Outline Design Stage was emphasised in section 3.10. This was the incentive for the focus on this design stage. However, the same section as well as section 5.5 and 5.5.3 also stress difficulties in a sufficient analysing of performance prediction at the Detailed Design Stage, which resulted in research efforts in this area.

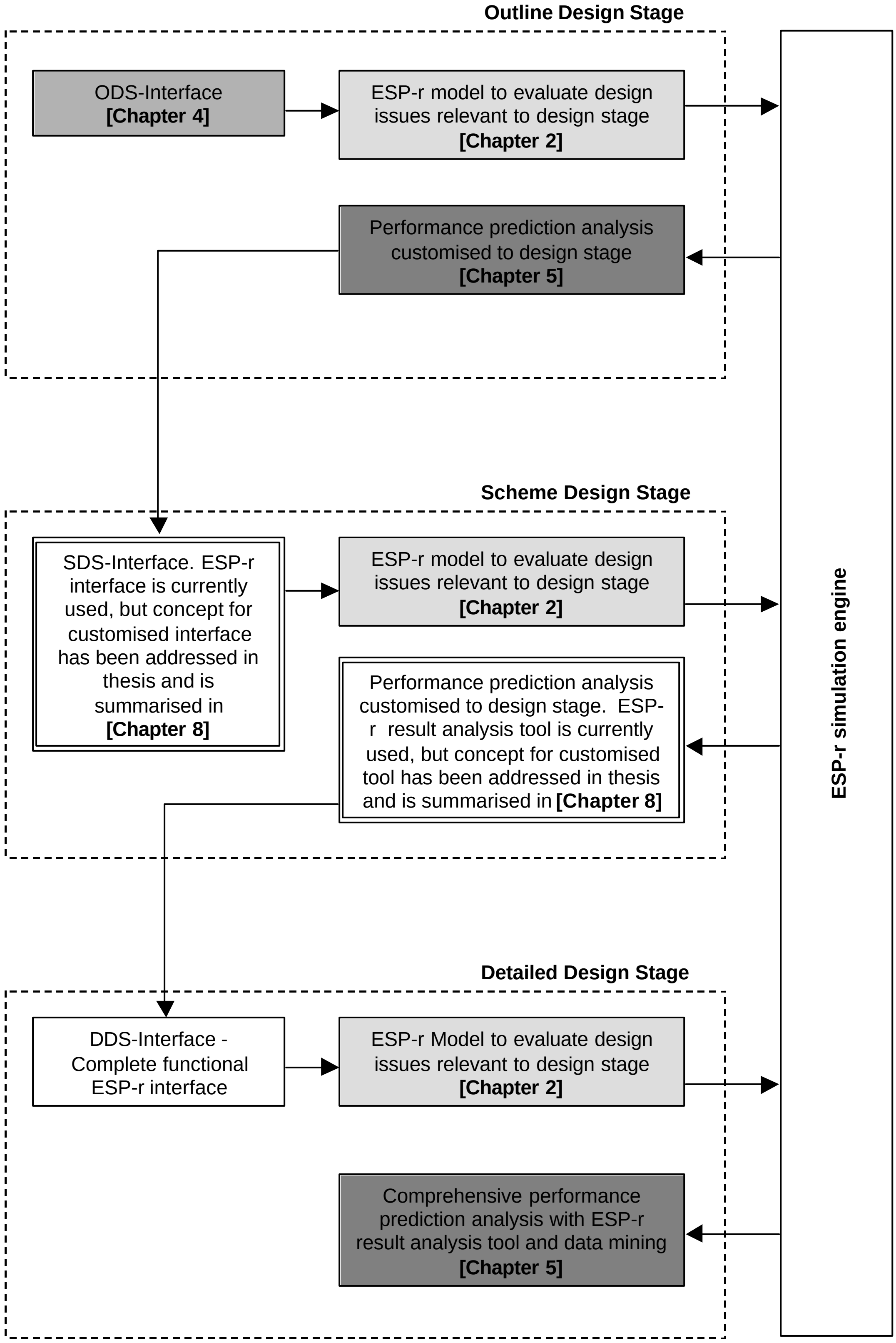


Figure 6.1: Enhanced application of simulation throughout the building design process

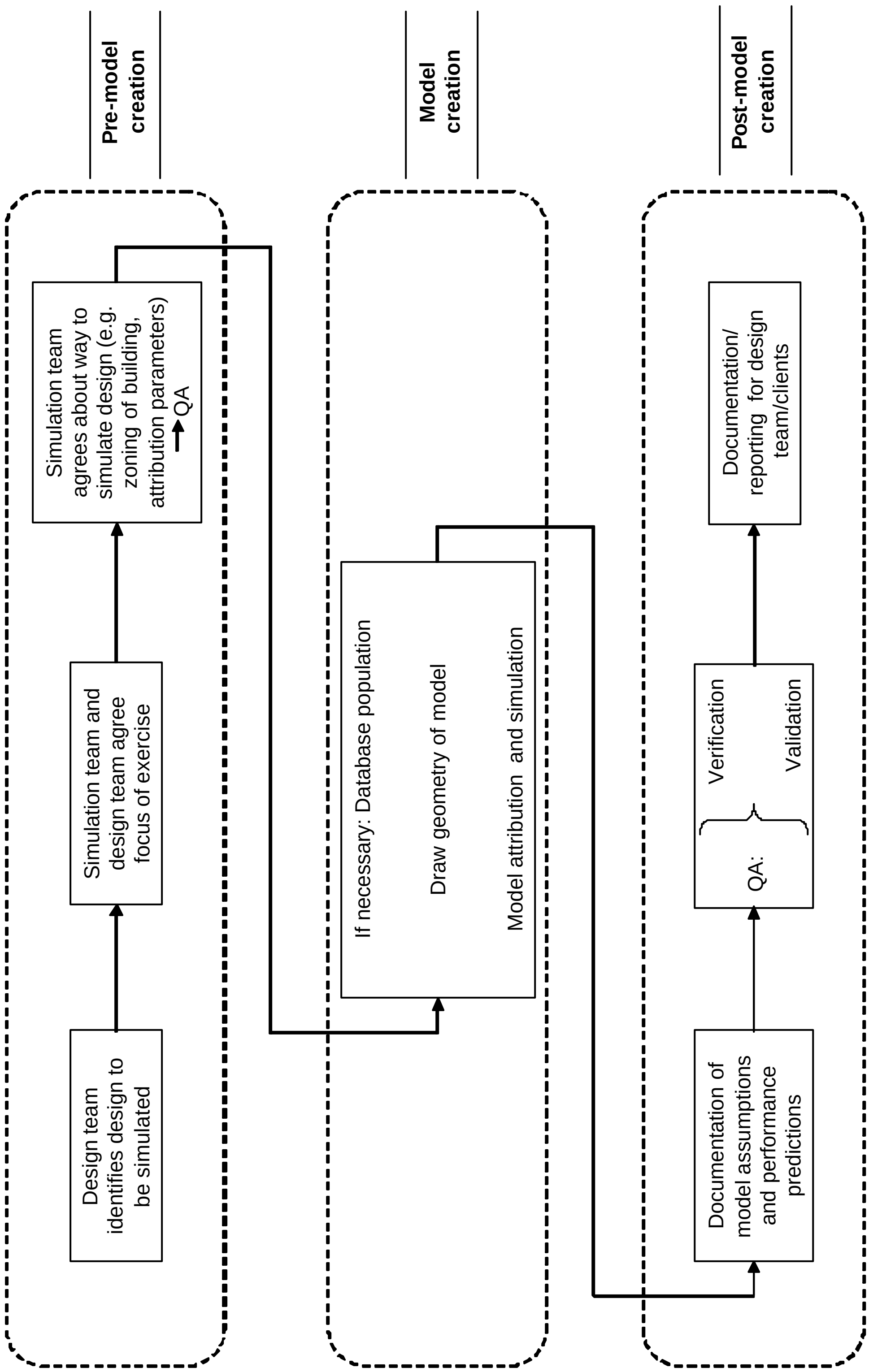


Figure 6.2: The process of creating and simulating a model

6.3 Implementation issues

Figure 6.2 displays tasks that have to be accomplished during a simulation exercise. The next pages discuss related implementation issues in more detail, with a special focus on the use of simulation at the Outline Design Stage, based on experience gained during the implementation of simulation within the architectural design practice where research for the SSDP was conducted.

6.3.1 Simulation project specification

A simulation project is normally initiated with a design team realising the need for an energy or environmental evaluation of a building design. The designers will then inform a simulation team about the characteristics of the design and state expectations about information they wish to obtain. Both parties then agree which simulation exercise(s) to carry out. This decision is based on the time required to carry out the exercise and the related cost, deadlines within which performance predictions need to be obtained, and resources available within the simulation team. In an architectural design practice this process is supported by management procedures which are covered later in this chapter (section 6.4).

Following this the simulation team agrees on a strategy for the simulation of the design. In this process the architects who use simulation again obtain support from external parties - such as simulation or building services experts - in order to assure an appropriate model definition. This issue is discussed in more detail in section 6.3.4, Quality Assurance (QA) of complete simulation model.

It cannot be expected from a design team that they automatically realise the benefits of a simulation exercise for a design projects. This is especially the case if the team members are not experts in energy and environmental design aspects. For this reason mechanisms have been put into place in the architecture company were simulation was implemented during the research that compel design team leaders to at least give consideration to the use of simulation. This happens by means of a section in the design management procedures (*not* simulation management procedures) were the project leader needs to sign of that simulation has been considered as a design tool (and reasons why it was found as not appropriate if it is not applied). In this decision making the project leader can obtain support from simulation and/or building services experts.

6.3.2 Simulation model creation

The simulation model creation involves the definition of the model geometry, the population of databases with new entities (if necessary) and the attribution of the model geometry to obtain a complete simulation model. This process differs between early and later building design stages. The ODS-Interface requires a complete geometry definition before the model attribution takes place – with the complete functional ESP-r Interface it is possible to carry out these the two tasks in parallel (see Figure 6.3).

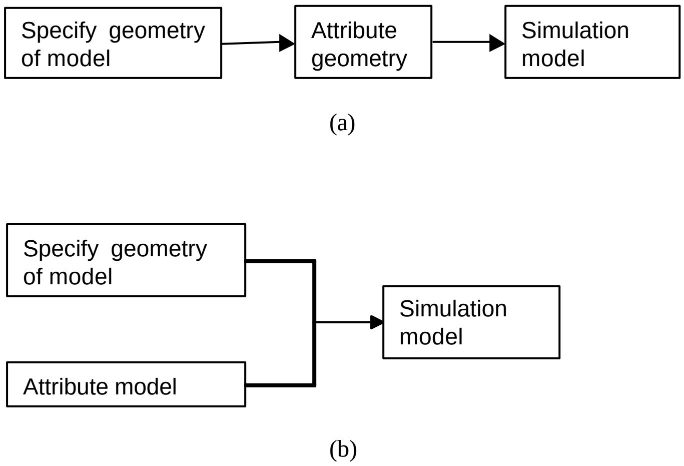


Figure 6.3: Model creation with the (a) ODS-Interface and (b) the complete functional ESP-r Interface

Requirements for database population will also differ between early and later design stages. At early design stages the input data is often not project specific but models are attributed using support databases that have been populated with industry standards because operational and control data has not been specified at that design stage. As a consequence, an extension of the databases is only required when a building has elements that do not comply with already specified entities or when the data definition is project specific. At later design stages the model data is in most cases project specific and hence database population will have to be carried out more frequently. The management procedures ensure that all entities which are included into the database are checked and documented.

6.3.3 Quality Assurance (QA) for geometry of ODS-Interface

With the ODS-Interface an incorrect geometry definition cannot be changed after it has been attributed it is therefore important to ensure that the geometry definition defined has been specified correctly before the attribution takes place. Later identification of errors can result in the need to redo a simulation exercise from scratch. This section describes control mechanisms that have been implemented to address this issue:

- a check of dimensions;
- a check that zones are properly bounded,
- a check that surface adjacencies have been specified correctly.

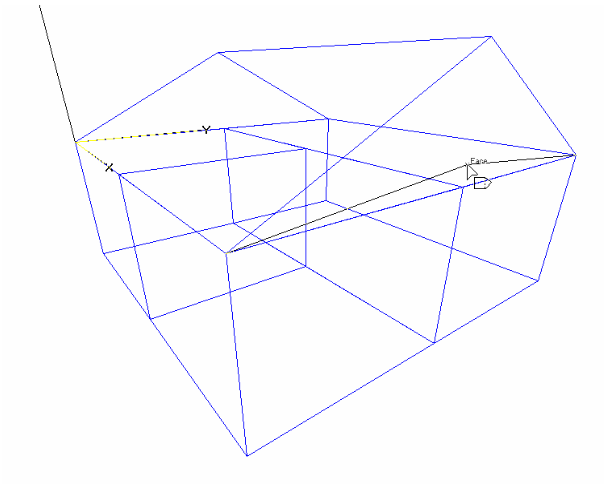


Figure 6.4: Inclusion of an additional vertex to ensure a properly bound zone

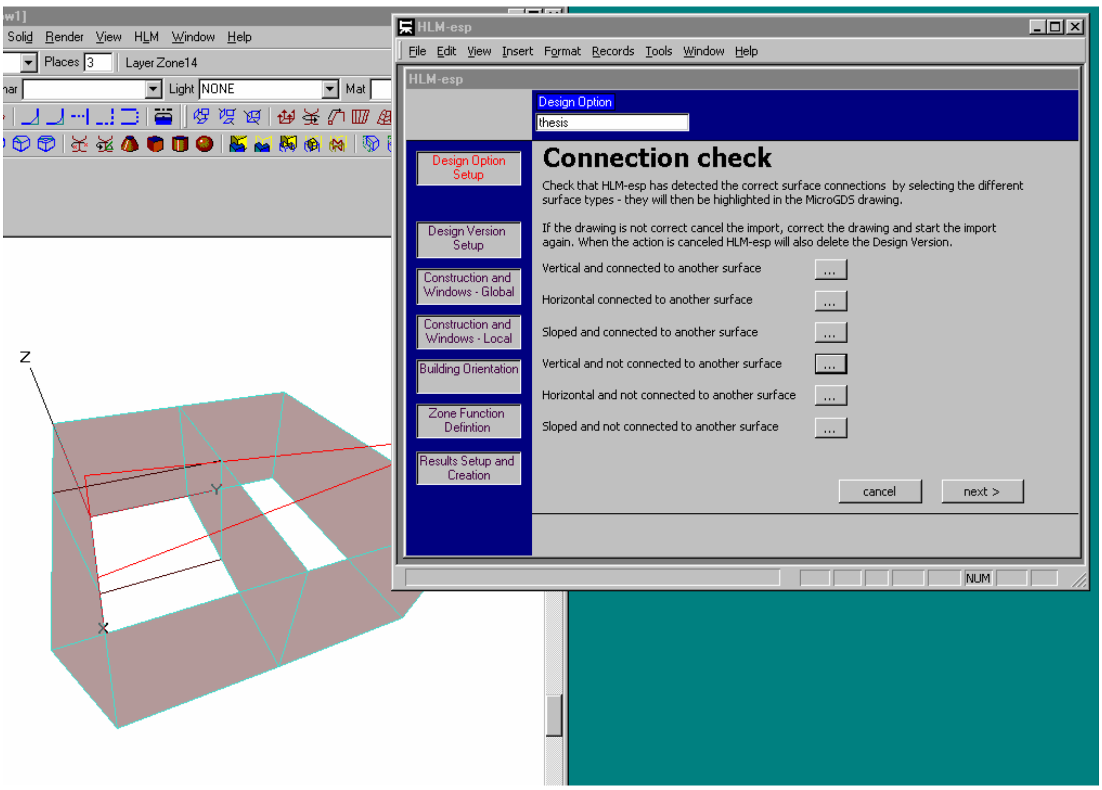


Figure 6.5: Incorrect definition of an internal surface (internal surfaces are detected as external)

A check of dimensions of the simulation model is aided by the fact that most models are based on existing design drawings. It is therefore possible to check a geometry definition by means of displaying this drawing simultaneously with the template drawing. Another necessary QA check is the confirmation that the CAD tool works in the correct units (e.g. metres rather than millimetres, which is the standard unit that architects work in) when the simulation geometry files are created from the CAD model.

Zones that have been created with standard 3D drawing functions from MicroGDS (e.g. extrusion of a 2D shape into a 3D zone) are generally properly bounded. Errors occur mainly when surfaces need to be split after an extrusion (e.g. to specify adjacencies to neighbouring zones). This can lead to errors such as missing vertices, surfaces that are drawn twice or have their vertices defined in the wrong direction [ESRU 2002]. These errors need to be identified. Figure 6.4 gives an example for an additional inclusion of a vertex into a surface.

The third check determines that all surfaces adjacencies have been specified correctly. The check is carried out in the ODS-Interface with the 'connection check'. It enables the user to view in turn different surface types by highlighting them in the CAD drawing. Selections are made based on the tilt of a surface and the environmental conditions on the other side, e.g. vertical and connected to another surface, vertical and not connected to another surface, etc. Figure 6.5 gives an example of the QA adjacency check.

All of the above listed checks have also been integrated into the management procedures and are carried out by a person who has not created the simulation model.

6.3.4 Quality Assurance (QA) of simulation model

QA checks of the simulation model form a vital part of every simulation exercise to ensure that the information produced is reliable [Law and McComas 2001, Fraedrich and Goldberg 2000]. Performance predictions need to correspond to the actual behaviour of the building. This check should be carried out as a combined verification and validation exercise. Verification and validation is defined as follows [Robinson 1994]:

Verification: ensuring that the designer is solving the *problem correctly*. This deals with the accuracy of transforming a problem formulation into a model.

Validation: ensuring that the designer is solving the *correct problem*. This deals with the model behaving with satisfactory accuracy consistent with the study objectives.

Verification and validation are illustrated in figure 6.6. Verification deals with the correct attribution of the simulation model. Validation is a high level check of the performance predictions obtained. The latter need not be performed by a simulation expert, but it is necessary that the person checking the model is familiar with aspects and considerations that formed the focus of the simulation exercise. This could be a building services engineer, environmental engineer or energy manager. It should result in the identification of significant errors in the model (e.g. 20 air changes/hour and not 2.0 air changes/hour) but also is an assurance that the model specification initially agreed where feasible (e.g. 6.0 air changes/hour may have been more appropriate than 2.0 air changes/hour). Without appropriate verification and validation, there is no point in carrying out a simulation project. Although these steps can be difficult and time consuming, a great deal of care must be put into these stages, otherwise decision-making based on the performance predictions obtained from the model can be risky.

Verification and validation are applied in the architectural simulation process by checks of the simulation models and also the involvement of additional parties into the simulation exercise (experienced simulation users, building services engineers or environmental engineers).

The experienced simulation users verify the simulation model data *before* and *after* its creation. The first check ensures that the model was created in an appropriate manner, the second check substantiates that the model was created as agreed. In addition to the benefit that by undertaking this check experienced users are incorporated into the model creation process, the exercise also ensures that a person verifies the built model who has not been involved in its creation.

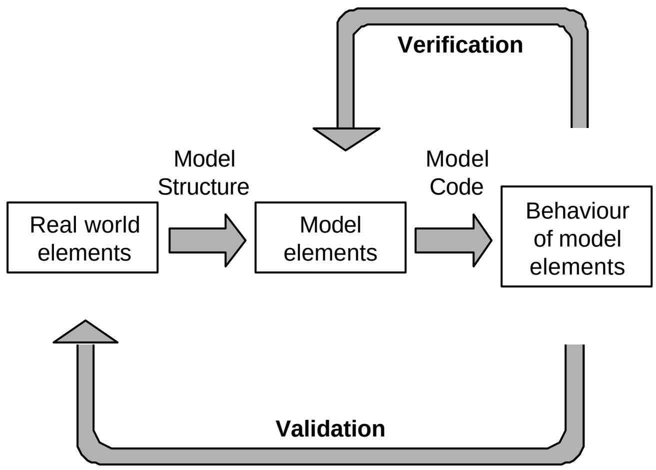


Figure 6.6: Verification and validation of a simulation model (after [Robison 1994])

Building services and environmental engineers can contribute to the verification and validation exercise in two ways: they can ensure that the input data for a model is appropriate (e.g. suitable internal heat gains and ventilation rates), but can also validate whether or not the performance predictions seem feasible. During the latter task they can apply range checks and use benchmark data that has been published for a similar building type, but can also apply their professional experience.

6.3.5 Expert involvement in QA

From the above description it was concluded that in order to ensure that a simulation model created will provide reliable results, knowledge and expertise from several experts (simulation, CAD, building services) is needed. To a certain extend this is caused by the fact that tools and functions required to carry out a simulation exercise have not been developed to a degree that a non-expert could carry out a simulation exercise independently. In case a CAD tool would automatically split all surfaces of a zone in a manner that allows the simulation tool to detect adjacencies between zones the QA check described in section 6.3.3 would not need to be carried out by a CAD expert. Similarly would the extensive population of zone function support databases with appropriate data for different room and building types (along with the development of algorithms that ensure that the appropriate support database items are linked to the different zones of a model) make the QA check of this model component by a simulation expert redundant.

Generally it can be envisaged that research and development in such areas will progress in the future. With efforts made by the Industry Foundation Classes (IFC, for a description see section 4.5.1) some CAD tools are for example already capable of semi automatically converting a CAD drawing into a geometry definition for a simulation model with all surfaces of a zone being split in a way that defines adjacencies.

Still, at the moment this is not the case, and hence expert input is required when carrying out a simulation exercise. In consequence it is likely that in the initial phase of the application of simulation by architects the tool will mainly be used by larger firms which can easier ensure that this input is provided. Such companies will either have experts in house or will be able to cover the cost for this input within their larger turnover. However, with improved facilities in the area of simulation it will be easier for smaller companies to carry out simulation exercises. With such a development becoming reality, simulation would take a similar route like CAD tools, which were in early days mostly used by larger companies for bigger projects.

6.3.6 Model documentation

The documentation of a simulation model forms an important part of a simulation exercise. It will support QA checks of the simulation model, but is also required for reports to the design team and clients.

One way of documenting a simulation model is by summarising its data in the form of a report. With the full ESP-r system it is possible to create a report that contains relevant data from the simulation files. The report is detailed but can be tedious to read due to the density of the format. The ODS-Interface can in addition produce reports with a structure tailored towards the conception of the ODS-Interface (e.g. global construction attribution, local construction attribution). This makes the report easier to read, but, unlike the report produced by ESP-r, it does not contain all of the data used for the simulation exercise. Appendix 3 gives an example of a report created by the ODS-Interface.

Apart from documentation in the form of reports, it is also important to include sufficient information in the simulation model itself so that a user can comprehend a model created by another user (e.g. when passing a model from one design stage to another). Such reporting facilities are also applied when a user creates a simulation model with the ODS-Interface. An example is the definition of descriptive zone comments which the user of the ODS-Interface specifies when importing a geometry. These definitions can later support a designer who views the model with the complete functional ESP-r interface (see Figure 6.7).

6.3.7 Management procedures for the use of simulation by architects

Management procedures have been specified for the application of simulation within the architectural practice (primarily they have been specified for the test bed company but could also be used by other practice) and these form part of the overall management procedures of the company. They ensure that simulation is applied in a controlled manner and also integrate simulation into the standard architectural work process. They address several issues:

- Provide a checking mechanism as to whether or not a simulation exercise is necessary – a simulation exercise should only be carried out if it provides an answer to a design consideration that cannot be answered in an easier and quicker way (e.g. by contacting a building services engineer).
- Ensure that financial and human resources required for the exercise are available.
- Agree deadlines that can be met by all parties and provide performance predictions in the time frame required by the design team.

- Ensure that data that has been used for the model creation is approved by either an external or internal party and that data sources (as well as the person(s) who approved the data) are documented.
- Ensure that the verification and validation exercises as described above are applied.
- Ensure that performance predictions are reported in an understandable way and that the report with the performance predictions explains the basis on which they were produced (e.g. input data used, model accuracy applied).

The management procedures have been developed in response to various considerations and needs. Firstly it was seen as important by members of the architectural company who were involved in the creation of the management procedures to make designers aware of all aspects of a simulation exercises (e.g. illustrate what simulation exercises can be carried out to support the designer, state financial and time implications for a projects budget when carrying out the simulation exercise, etc.). They argued that this was especially important now at early days of the use of simulation by architects when the tool is still unknown to the design team. The management procedures have therefore educational functions but also prevent confusion and frustration among designers (e.g. a simulation exercise could be more costly than the designer anticipated) which may counteract the aim to increase the use of the tool.

A second aim was to ensure that performance predictions obtained from a simulation exercise are feasible. These sections of the management have been produced based on previous experience by simulation experts in this area (e.g. University of Strathclyde/ESRU) or by publications in this field (e.g. [BRE 1999]). However, they still also had to be tailored towards the requirements of an architectural design practice (e.g. ensure input is made from simulation experts when required, new database entities are QA checked). Appendix 4 shows as example pages the section of the management procedures for a simulation exercise request by the design team.

Such management procedures should generally be specified whenever simulation is applied within the building design process. However, they are especially important when the tool is applied within an architecture company, where the designers are not experts in the use of the tool and also use it infrequently.

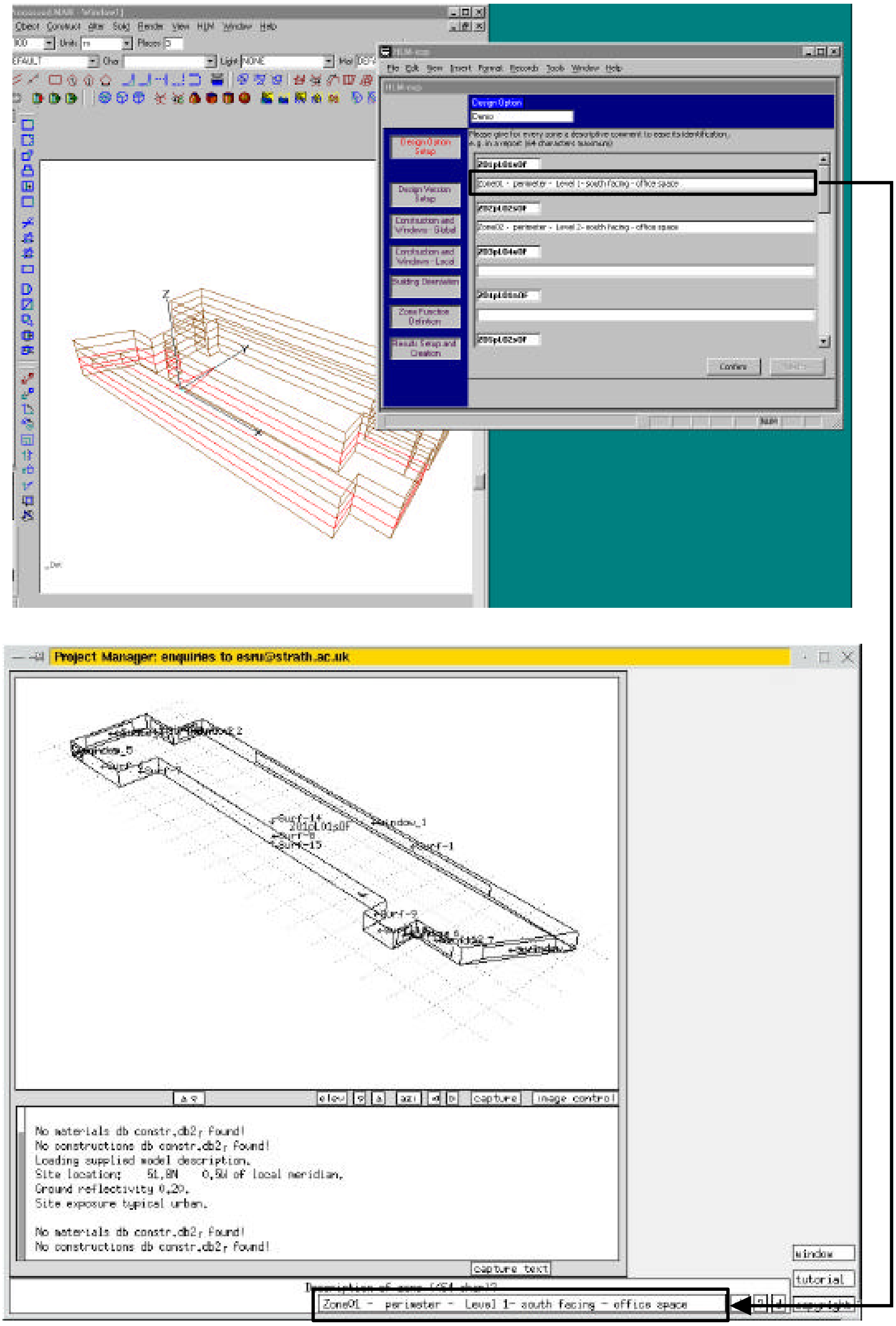


Figure 6.7 Descriptive zone comments are specified during the geometry import of the ODS-Interface and are later available with the full ESP-r system

Generally the use of management procedures can slow down the speed with which a simulation model is created (additional work required to fulfil the tasks involved, waiting for response from person carrying out a QA check), but it has to be ensured that they are always applied. One way to ensure this is by linking them to the simulation tool (management procedures open up automatically in a text document when a designer starts the simulation interface). This feature is currently under development for the ODS-Interface.

6.3.8 Training of architects in the use of simulation

Appropriate training of the architect carrying out a simulation exercise is required to ensure the efficient use of the tool and the creation of appropriate simulation model. Basic training in the operation of the CAD tool for the specification of a model geometry as well as the ODS-Interface for its attribution can be carried out after less than a of day (this was an observation made when training more than 15 architects on the use of simulation during the research). After that users can operate the system. However, they will still need support when they start using the tools on real projects. This support can relate to more detailed aspects of the operation of the ODS-Interface or CAD tool (e.g. how to specify a local surface property) but more frequently will relate to simulation in general (e.g. how to specify a zoning strategy or select appropriate zone functions). Questions regarding the use of the CAD tool and ODS-Interface are normally resolved after the architect has used the tool on one or two projects, but issues that relate to simulation in general will require longer training support.

However, over time this training will remove the black box appearance from a simulation exercise. At some point users of the ODS-Interface could then be sufficiently experienced to get involved in tasks where a greater degree of understanding for simulation is required. Examples would be simulation exercises with the fully functional ESP-r interface or wider database population for the ODS-Interface.

Training is currently carried out by in-house training, support during project work as well as through an extensive user manual which explains the user functions of the tool in detail.

6.3.9 Liability

When using simulation throughout the design process different designers will carry out the assessments using simulation. At early building design stages it will be architects who specify a simulation model, later on other designers such as building services engineers may use the model created by the architects as a basis for their building performance appraisal.

With the application of simulation architects get involved in areas were they had previously limited responsibility because they start making statements about the energy and environmental performances that can be expected from a building. Traditionally these issues were dealt with by building services engineers. This raises questions related to liability:

- To what extent is the architect responsible for the performance predictions obtained in early design stage studies?
- When does the building services engineer take over the ownership of a simulation model?

These issues will be discussed in the next chapter in section 7.4, "Observations from a survey of designers".

6.4 Closing remarks

This chapter first illustrated how research and developments introduced in earlier chapters of this thesis can make contributions towards a design situation where simulation is better integrated into the building design process. It then discussed implementation issues with a special focus on the early building design stage. It covered model creation and Quality Assurance issues and how they are supported by model documentation, management procedures and training.

Finally the chapter introduced the fact that the use of simulation by architects raises liability questions. This part of the chapter emphasises the fact that in addition to research and developments described in earlier chapters support needs to be provided for the integration of simulation into the building design process to ensure several issues:

- ensure that the tools are used efficiently but rules are still followed that ensure their use in a controlled manner;
- make the process transparent how simulation should/can be used as part of the building design process (especially or relevance when architects use the tool, see section 6.3.7);
- ensure that the simulation model created will provide performance predictions which are sufficiently accurate;
- train staff that they acquire skills required to carry out a simulation exercise.

It was also said that in early days of the use of simulation by architects these support requirements make it likely that the tool will mainly be used by bigger companies, but it was also reasoned that over time smaller companies might also be capable of deploying simulation.

The next chapter illustrates the application of simulation in the building design process with case studies and feedback given by designers who were involved in the use of simulation at early building design stages.

References

BRE, "Quality Assurance Procedures for use with Building Energy and Environmental Modelling Software", draft report by BRE / Centre for Construction IT, 2002.

ESRU, "ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series", University of Strathclyde, Glasgow, 2002.

Fraedrich D, Goldberg A, "A Methodological Framework for the Validation of Predictive Simulations", European Journal of Operational Research, Volume 124, pp55-62, 2000.

Law A M, McComas M G, "How to Build a Valid and Credible Simulation Model", Proceedings of the 2001 Winter Simulation Conference, Arlington, VA, 2001.

Robinson S, "Successful Simulation – a Practical Approach to Simulation Projects", McGraw-Hill Book Company, 1994.

CHAPTER 7

CASE STUDIES AND FEEDBACK FROM DESIGNERS

7.1 Introduction

This chapter demonstrates how the developments previously described are brought together to facilitate the key objective of this thesis: the integration of simulation into the building design process. The first part of this chapter contains case studies based on design projects of the architecture company that formed the research bed for the development of the SSDP and the implementation of the ODS-Interface.

By implementing simulation into the Outline Design Stage of the building design process it was also possible to obtain valuable feedback from practitioners about the use of building simulation at early design stages. This feedback was gathered in the form of surveys of designers who operated the ODS-Interface and also from designers who used performance predictions obtained from simulation exercises for strategic design decisions. Survey results are presented in the second part of the chapter. This is followed by feedback from two building simulation consultants about their view of advantages of employing simulation for building analysis.

7.2 Case studies

The following sections describe three different case studies. The first two illustrate the benefits of using simulation at early building design stages; the third shows how the structured application of simulation throughout the design process can result in more informed decision making and enhance the quality of the building design.

7.2.1 Case study 1: House block in prison

The first case study describes how simulation was applied for the evaluation of energy and environmental implications of design alterations to the design of the house block of a prison building. Prisons are buildings with construction materials and occupancy behaviour which are distinctly different from 'normal' buildings. The cells have a fairly small floor area and are enclosed by concrete walls. They can be occupied for most of the day and can have considerable internal heat gains from occupants, equipment and lighting. For security reasons the windows are single glazed and fresh air is provided by a ventilation grille underneath the window. All of this creates a situation where the energy and environmental performance of the building is influenced by quite unique conditions. Also, design support from simplified simulation tools or design guidelines is difficult to obtain, because these EEDDSS normally do not cover this particular building type[1]. The ODS-Interface made it possible to fill this gap.

In this particular case the designers used the ODS-Interface for two different exercises:

- to identify heat loss paths from the building in order to assess the effectiveness of energy conversation measures and
- to assess the impact of the cell orientation and occupancy density on the resultant temperature in a cell during summer.

Simulation model

The house block of the prison was cross-shaped (see Figure 7.1) with identical conditions in each wing (apart from the window orientation), allowing the simulation of one wing as representative for the conditions in the building in general (window orientation can be considered as a design parameter by altering the orientation of the building).

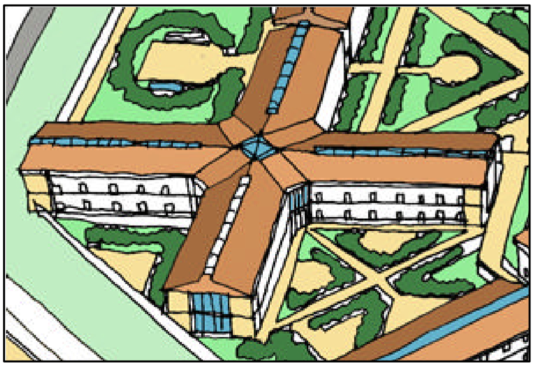


Figure 7.1: A house block in a prison

Figure 7.2 shows images of the 13 zones simulation model that was used for the assessment. The wing is 25.0 m long and 16.5 m wide. It has a central circulation area with rooms on either side. These are mainly cells, but also a kitchen, laundry and two bathrooms. The external walls are cavity walls with an inner layer of concrete and an outer layer of brick. Partitions and intermediate floors are concrete constructions. 10% of the façade is glazed. The cells, kitchen and bathrooms were specified in the model to be heated to 21ºC

[1] Although such an evaluation could of course be carried out with advanced simulation tools like the Building Design Advisor.

between 6:00h and 22:00h and 16ºC between 22:00h and 6:00h[1]. The central circulation area is constantly heated to 21ºC. Internal heat gains were defined as typical for the usage function of the different zones. Ventilation rates were specified at 2.5 air changes per hour with exception of the central circulation area, which was defined to be ventilated with 1.0 air changes per hour (this data was provided by building services engineers). Self shading of the building or shading of the window from bars was not considered in the model (although solar data was generally considered by the simulation engine).

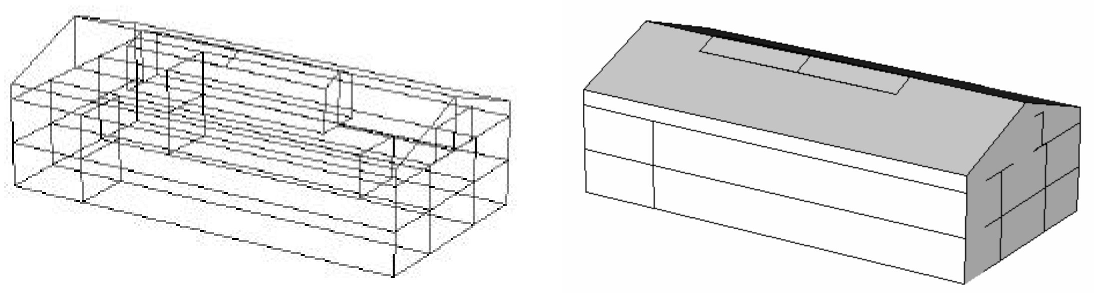


Figure 7.2: The geometry of the simulation model

Energy study

To determine the heat loss paths from the building, four Design Versions as described in Table 7.1 were created. The insulation of the opaque building envelope of Design Version 1 (as built) is in compliance with the Building Regulations pre-April 2002, the single glazing is required to comply with security requirement for a prison building and the ventilation rate was provided by the building services engineers as typical for a prison building. Based on Version 1 three other Versions were created to evaluate implications of different heat loss paths on the energy consumption in the building.

Design Version	**U-value façade** *[W/m²K]*	**U-value roof** *[W/m²K]*	**U-value Glazing** *[W/m²K]*	**Ventilation rate in call** *[ac/h]*
1. As built	0.45	0.33	5.44	2.5
2. Better insulated opaque envelope	0.26	0.18	5.44	2.5
3. Double glazing	0.45	0.33	2.78	2.5
4. Reduced ventilation rate	0.45	0.33	5.44	1.0

Table 7.1 The different Design Versions of the energy study

[1] The HLM -esp support databases specify heating (and cooling) control as an unlimited plant capacity and assuming ideal control. It was found that this is sufficient for early building design stages. If necessary more detailed data can however be defined at later, more detailed design stages.

Table 7.2 lists the energy consumptions that were predicted from the simulation exercise. It can be seen that the increased insulation level of the opaque building envelope reduces the heating energy consumption by only 4%. Changing the glazing from single to double-glazing would reduce the energy consumption by 10%. However, the biggest savings result from the reduced ventilation rate, which reduces the heating energy consumption by 25%. This shows that one of the most likely choices of an architect when aiming to reduce the heating energy consumption of the building (upgrading the opaque building envelope) in this particular design situation brings very limited benefits. Changing the single glazing to double-glazing would be significantly more beneficial but is not possible. The biggest potential clearly lies in the recovery of heat from the air that is removed from the building via ventilation.

Design Version	**Heating Energy Consumption *[kWh/m²a]***
1. As built	154
2. Better insulated opaque envelope	148
3. Double glazing	139
4. Low ventilation rate	116

Table 7.2 Heating energy consumptions predicted

Comfort study

Further simulations were undertaken with the aim of assessing the impact of the cell orientation and occupancy density on the comfort conditions in a prison cell. These considerations were of interest since with the cross-shaped footprint of the building a cell can face in any direction and also due to the fact that under certain circumstances it is possible to have two occupants per cell which results in higher occupancy densities.

Table 7.3 lists the different Design Versions that were created. The window orientation was defined as south-west or north and the occupancy density as 11 m^2/occupant or 7.2 m^2/occupant (140% increased density with two occupants in a cell – the data was given by the designers).

Design Version	**Window Orientation**	**Occupancy Density**
1) SW facing cell with normal occupancy	South West	11 m^2/occupant
2) N facing cell with normal occupancy	North	11 m^2/occupant
3) SW facing cell with 140 % occupancy	South West	7.8 m^2/occupant
4) N facing cell with 140 % occupancy	North	7.8 m^2/occupant

Table 7.3 The different design version of the comfort study

Figure 7.3 shows for the different Design Versions the frequency binning of resultant temperatures within the cell above a value of 24 ºC. It can be seen that both the orientation and the occupancy density have a noticeable impact on the temperature conditions in the cell. In consequence it was concluded that cells that face the sun should only have a single occupancy density.

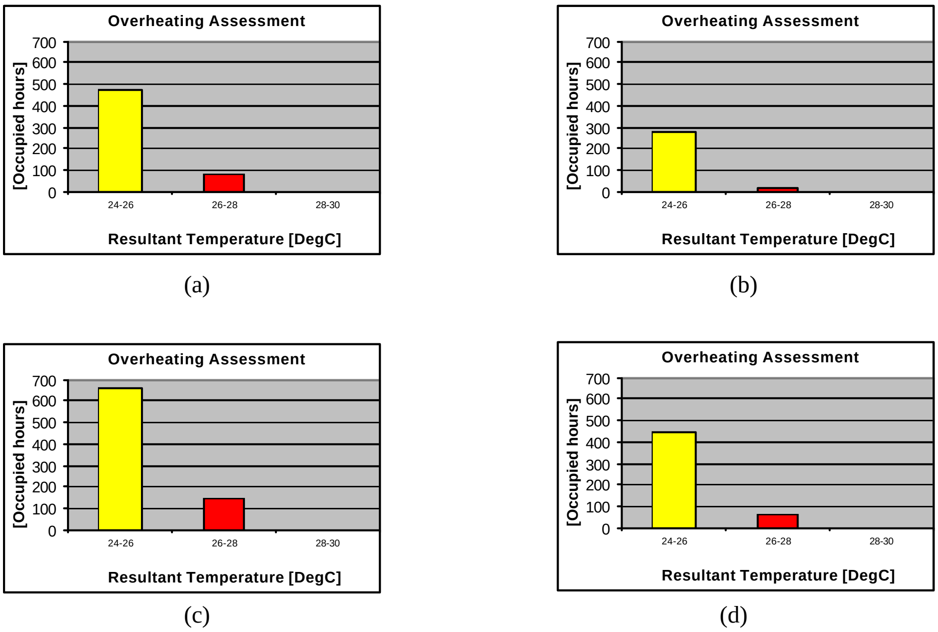


Figure 7.3: Resultant temperature in prison cells with different window orientations and occupancy densities: (a) South/west facing window, normal occupancy, (b) North facing window, normal occupancy, (c) South/west facing windows, high occupancy, (d) North facing windows, high occupancy

In Figure 7.4 it can be seen that the simulations predicted temperature variations of less than 3 ºC over a daily cycle, resulting in small temperature drops during the night time. A second observation is that in times of extreme high ambient temperatures the internal temperature is below ambient.

Discussion of case study

Easy to use computerised EEDDSS normally would not enable building designers to evaluate the energy or environmental performance of a prison building at early design stages. The development of the ODS-Interface has made this possible. Both simulation studies were carried out in less than a day by the architects themselves, producing performance predictions of an exceptional building type in a short time without relying on external consultants.

It was also interesting that the predicted temperature profiles over the daily cycle were also observed in already built similar house blocks (Sharples [2002], the corporate manger of the Prison Blackenhurst, made this observation when viewing the performances predicted by the simulation exercise). This showed for this particular simulation run the accuracy of performance predictions obtained by applying advanced dynamic simulation.

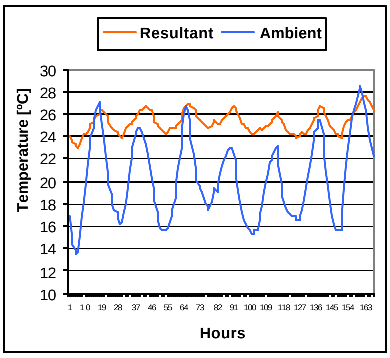


Figure 7.4 Ambient and resultant temperature for Version 1 in a hot summer week

7.2.2 Case study 2: Part L compliance study

The second case study describes a simulation exercise that assessed whether or not a proposed building design could achieve compliance under the Carbon Emission Calculation Method of the British Building Regulations Part L [DTLR 2002]. With this method, the calculated annual carbon emissions for the proposed building should not be greater than those from a notional building of the same size and shape designed to comply with the Elemental Method of the Building Regulations.

Simulation model

The simulated building comprised 13 floors (see Figure 7.5). The bottom floor was used as a retail area. The floor above was used as the lobby of the building. On top of this were 11 floors that were used as office spaces. Floors that had identical thermal conditions were represented by one floor and the results were scaled up. Each floor comprises an occupied space with a height of 2.75m and a void space 1.1 m high. For the model representing the proposed building the glazing area of the occupied space was specified as 90% and for the notional building as 61.1% (equivalent to 40% overall façade area). The windows in the proposed building were attributed as double-glazing, in the notional building as glass with a

U-value of 2.2 W/m^{2}K (required by the Building Regulations [DTLR 2002]). Fresh air was supplied at 16 l/s per person, assuming a 50% heat recovery. Internal heat gains were specified as typical for an office building [CIBSE 1998].

Results

The study was carried out in two steps. First the building was simulated with the ODS-Interface described in chapter 4 to determine the heating and cooling energy requirements as seen by the building plant as well as the required capacities. Table 7.4 shows this data for the notional and the proposed building design.

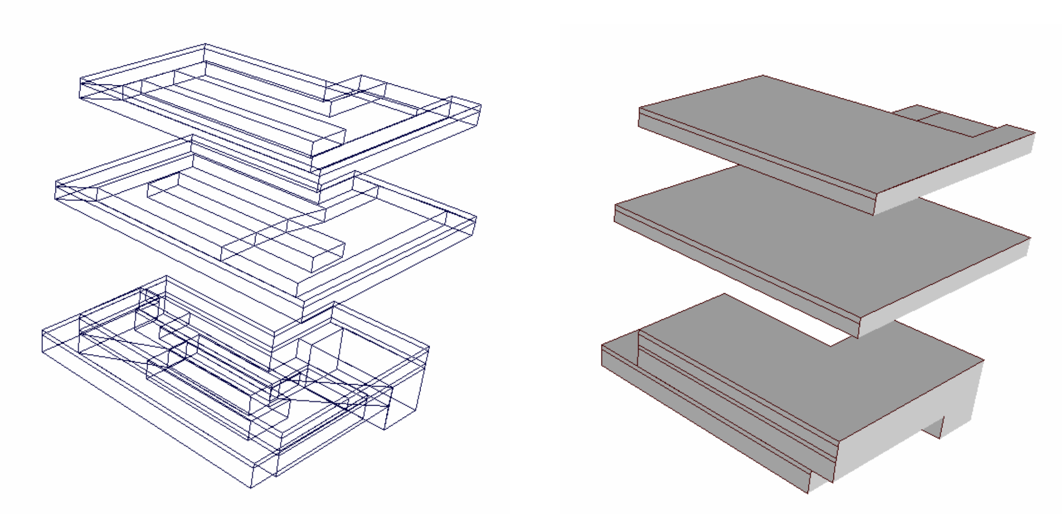


Figure 7.5: The geometry of the simulation model (missing areas are floors reproduced using zone scaling)

	Notional Building	Proposed Building
Heating Energy Consumption [kWh/m^{2}a]	7.5	11.1
Cooling Energy Consumption [kWh/m^{2}a]	63.2	60.5
Heating Capacity [kW/m^2]	30.5	35.5
Cooling Capacity [kW/m^2]	61.8	70

Table 7.4: heating and cooling energy requirements as seen by the building plant and required plant capacities

It can be seen that that the notional building has a lower heating energy consumption than the proposed building but a higher cooling energy consumption. This was a surprising finding because it was initially assumed that the higher solar gains caused by the larger glazing areas of the proposed building would result in higher cooling energy consumption. In consequence it was decided to pass the model to the full ESP-r system where a more detailed performance prediction analysis could be carried out.

Figure 7.6 displays a first finding from this analysis. The graph displays the heating and cooling loads in the zones on the level that was simulated as representative for most of the office spaces within the building. It can be seen the building has a significant cooling load throughout the year, whereas the heating load is generally low. The glazed areas with their lower thermal resistance are an important heat flow path. In this particular case the large glazing area therefore reduced the cooling load of the building. This finding was also confirmed by a detailed analysis of the energy breakdowns that occur in the different zones during various climatic conditions.

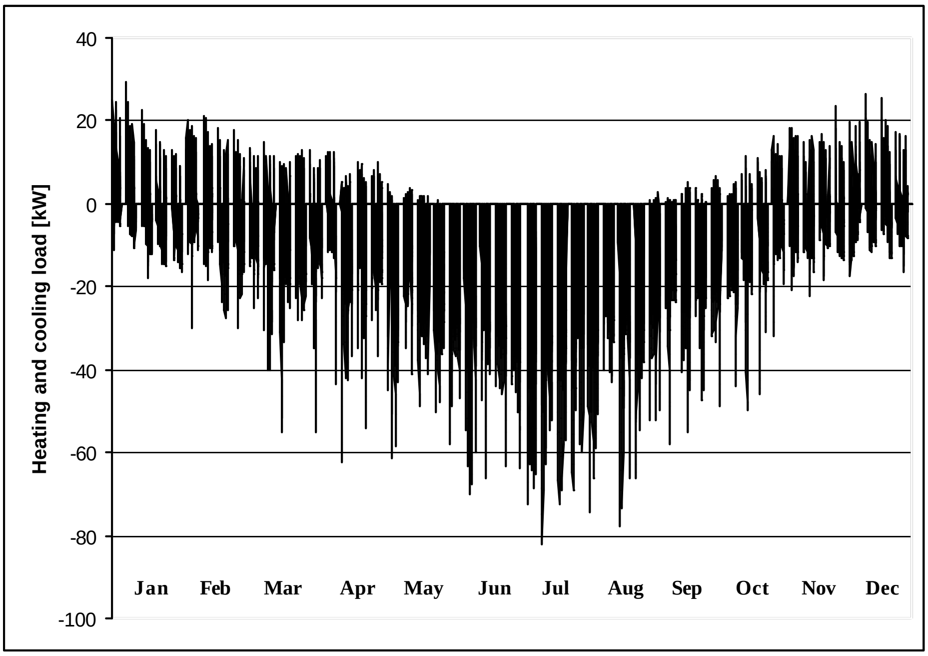


Figure 7.6: Heating and cooling loads in selected office spaces (perimeter and core location) of the proposed building over an annual period

However, although the building envelope did not negatively influence the energy performance of the proposed building the notional building still had lower energy consumption. This was a result of the plant system that was specified for this particular building (See Table 7.5). The building could still achieve compliance based in the *Whole-building Method* because its overall carbon emissions were lower than the benchmark specified in the Building Regulations.

Building type	Heating	Hot water	Cooling	Auxiliary plant	ACMV[1] fans	Lighting	Office equipment (small power)	Total
Notional	7	4	33	11	47	43	30	176
Proposed	11	4	38	38	60	39	30	220

Figure 7.5: Annual delivered energy consumption [kWh/m^2]

Discussion of case study

The second case study showed again how the integration of simulation into an early building design stage resulted in a more informed decision process. It was shown that for this particular building large glazing areas did not cause a higher energy consumption than a notional building with smaller glazing areas. This was a finding that contradicts best practice advice as well as the design approach that the Building Regulations try to encourage with the elemental method. Using simulation thus informed the designer that in this particular case it is possible to make the preferred aesthetic design choice without this resulting in increased energy consumption in the building. Without the application of simulation the designer might not have considered such as design, knowing that it would not pass on the basis of the Elemental Method of the Building Regulations. However in this particular building design failed in its overall performance because of its high energy demands by the plant system.

7.2.3 Case study 3: Application of simulation throughout the design process

The third case study, based on an office development, illustrates the benefits of using simulation throughout the design process. The exercise followed the simulation concept outlined in chapter 3 and applied the ODS-Interface, the full ESP-r system and data mining.

Simulation model

Figure 7.7 displays the simulation model that was used for the building performance evaluation [2]. The building is four storeys high, 91 m long and 51 m wide and has a central atrium. The office spaces have an occupancy density of 12.5 m^2 per occupant; the resulting minimum fresh air requirements are 1 air change per hour. In most areas small power loads emit 10 W/m^2 internal heat gains, but there are also areas with 25 W/m^2. During weekdays the offices are fully occupied from 8:00h until 18:00h and partially occupied from 18:00h

[1] Air conditioning and mechanical ventilation fans

[2] To reduce the complexity of the case study the exercise did not include the evaluation of different building geometries.

until 20:00h. Lighting is assumed to emit 10 W/m^2 [1] between 8:00h and 18:00h and 5 W/m^2 from 18:00h and 20:00h. The atrium is occupied daily from 9:00h until 19:00h (if internal temperatures allow occupancy since the space is not heated). The designers aimed at a heating energy consumption lower than a good practice office building (see [BRESCU 2000] for indicators of typical energy consumptions) and at achieving summer comfort conditions with minimum artificial cooling, ideally none at all.

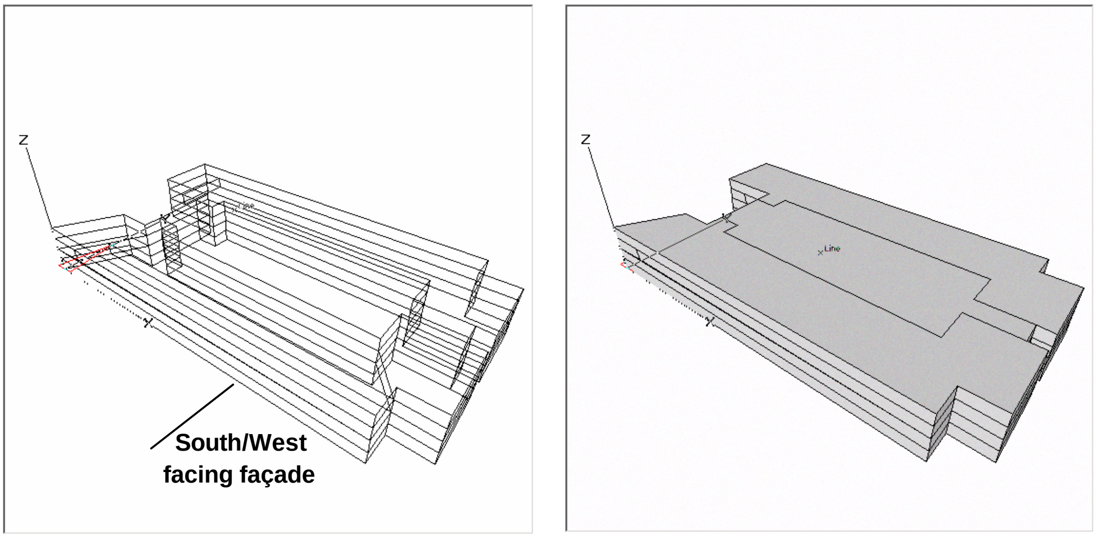


Figure 7.7: The geometry of the simulation model

Outline Design Stage

At the Outline Design Stage simulation was applied to determine several key performance indicators:

- heating energy consumption in the building;
- summer resultant temperatures in office space;
- summer resultant temperatures in atrium.

Resultant temperatures were determined for a SW facing perimeter zone on level 3 and the lower zone of the atrium (see Figure 7.8). The perimeter zone was chosen because it is exposed to solar gains and the lower zone of the atrium is the occupied space of this building section.

[1] The value of 10 W/m2 was found to be an appropriate value for heat emitted from an average lighting system in an office.

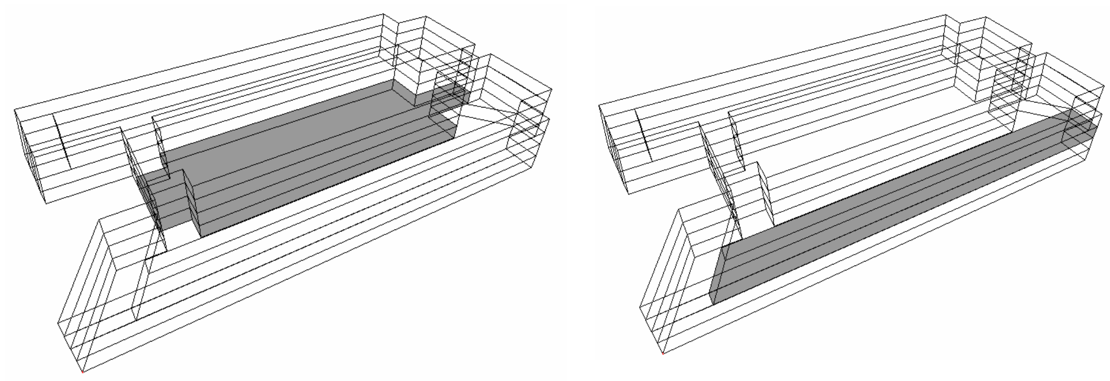


Figure 7.8: The zones in which resultant temperatures were determined

The design team identified different design changes that might or might not influence/improve the building performance:

- Different insulation levels of the building envelope could influence the heating energy consumption.
- The window size in the office spaces will probably influence both the heating energy consumption and the summer temperatures.
- Solar control in the office spaces and atrium could reduce the summer temperatures.
- Increased ventilation rates in the office spaces and atrium could reduce the summer temperatures.
- An increase of the building mass in the office spaces and atrium could reduce the summer temperatures.
- Positioning the spaces with high internal heat gains at the façade could potentially increase the overheating problem because of combined equipment and solar gains.
- Changes in the air infiltration rate (depending on the airtightness of the building envelope) can influence the heating energy consumption.
- Heat recovery systems could reduce the heating energy consumption.

Table 7.6 lists the model parameters with which the above design variations could be compared. The grey boxes contain parameters which were identified as likely to provide a building with a good energy and environmental performance (for thermal mass, heat gains from equipment and solar control design specifications were chosen that will improve the summer comfort conditions in the space in order address the request for minimum or no air conditioning).

Window size office	40% of façade	90% of façade	
Heat recovery system[1]	Excluded ? 1 air changes/hour	Included ? 0.5 air changes/hour	Office
Insulation of envelope	Facade 0.35 W/m^{2}K / Roof 0.25 W/m^{2}K	Facade 0.17 W/m^{2}K / Roof 0.12 W/m^{2}K	Office
Thermal mass	Raised carpet floor and suspended ceiling	Exposed floor and ceiling	Office
Summer ventilation rates	1.0 air changes/hour	4.0 air changes/hour	Office
Heat gains from equipment	10 W/m^2	25 W/m^2	Office
Solar control	None	External blinds	Office
Summer ventilation	0.75 air changes/hour	3.0 air changes/hour	Atrium
Solar control	None	External blinds	Atrium

Table 7.6: Different model parameters

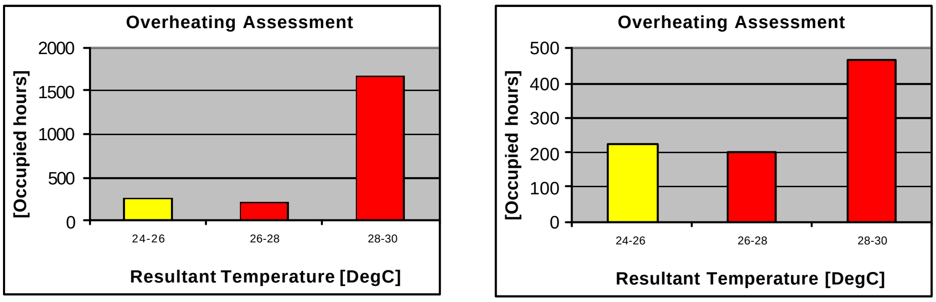
An initial assessment was carried out by creating a base case that produced benchmarks for the different energy and environmental performance indicators. For this purpose the simulation model was attributed with parameters which could be expected lead to poor building performance (white boxes). The reason for focusing first on these design parameters was that they were preferred by the designers for various reasons: aesthetics (large glazing areas), less costly construction cost (minimum insulation requirements given in the building regulations, no heat recovery), and following of conventional design choices (suspended ceiling and soft floor finishing, ventilation for fresh air requirements rather than for cooling purposes). The performance was then compared against good practice benchmarks. Poor performance could be improved by changing design parameters listed in Table 7.6 (to design parameters specified in the grey boxes).

Table 7.7 list the attributes that were chosen for the base case Design Version. Figure 7.9 shows predictions for the resultant temperatures in the office space and atrium. The predicted heating energy consumption required in the building was 45 kWh/m^{2}a.

Atrium		**Office space**						
Summer ventilation	Solar Control	Window size	Heat recovery	Insulation	Mass	Summer ventilation	Heat gains	Solar control
Low	No	Large	No	Low	Light	Low	High	No

Table 7.7: Attribution of base case Design Version

[1] Assuming 50% efficiency



(a) (b)

Figure 7.9: Annual resultant temperature in different spaces of the building obtained in initial simulation: (a) office space (b) atrium

This energy consumption was well below good practice benchmark figures for heating (91 kWh/m^{2}a). Even taking into account plant inefficiencies the metered energy consumption would still be below this benchmark. However, it can be seen that the resultant temperatures lead to poor comfort conditions for long periods in both the atrium and the office space. Overheating was therefore identified as the focus of further simulation studies at this as well as later design stages.

To assess how far the poor performance with regards to the aesthetics could be improved by the design measures outlined in Table 7.6 a second Design Version was created in which parameters were chosen that should improve the summer performance. Table 7.8 lists the parameters; Figure 7.10 shows the frequency distribution of the temperatures.

It can be seen that in both the atrium and the office the resultant temperature has dropped significantly (in addition did the heating energy consumption only rise from 45 to 55 kWh, which was still considerably lower than the benchmark specified).

For the office space it was not clear what design parameter had caused this temperature reduction. However, this was important to know because some parameters (e.g. window size) would not be changeable at later design stages. In consequence a study was carried out where each of the relevant parameters was changed in turn. With the ODS-Interface such changes could be carried out in a structured manner and within minutes by creating copies of Design Versions and only changing the relevant attribution(s) (e.g. global specification of the window size). Figure 7.11 shows the temperatures that were obtained from this study. It can be seen that the smaller window size reduced temperatures above 28ºC by 8%, blinds led to a reduction by 14%, low internal heat gains by 15%, a change to heavy mass by 26% and high ventilation rates by 37%. Considering the objective outlined in the initial brief (minimum or no air conditioning) and the fact that all changes had made a considerable contribution to better summer comfort conditions it was decided to keep the attribution from the second Design Version as part of the building design.

For the atrium no further studies were carried out. It was sufficient that simulation had identified the overheating problem but also that for this part of the building a combination of solar control and higher ventilation rates could eliminate it. With more detailed studies in the Scheme Design Stage the exact shading and ventilation requirements could be defined.

Atrium		Office space						
Summer ventilation	Solar Control	Window size	Heat recovery	Insulation	Mass	Summer ventilation	Heat gains	Solar control
High	Yes	Small	No	Low	Heavy	High	Low	Yes

Table 7.8: Attribution of second Design Version

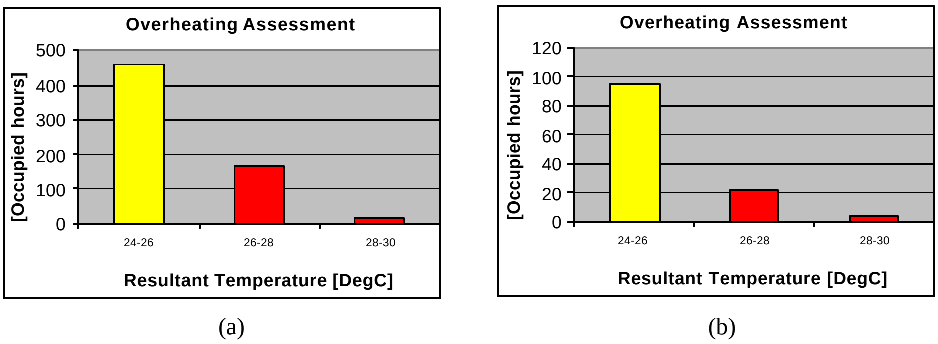


Figure 7.10: Resultant Temperature in different spaces of the building obtained after design changes to improve thermal performance: (a) office space (b) atrium

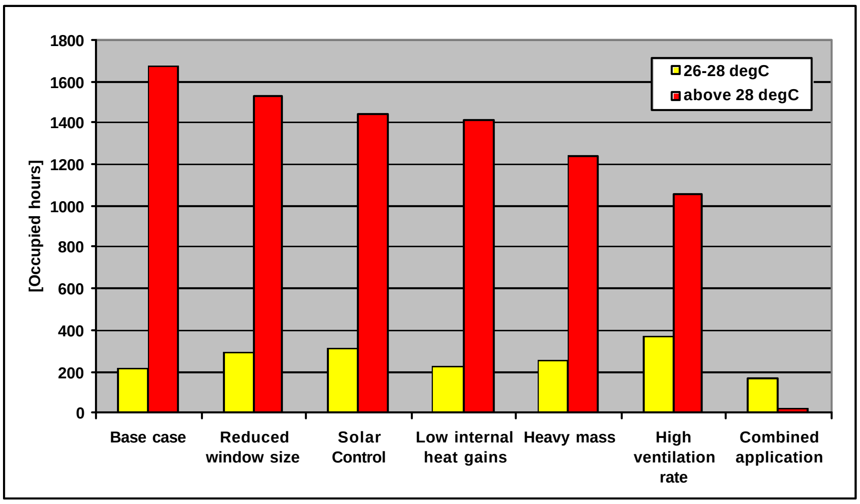


Figure 7.11: Resultant temperature in office for different Design Versions

Scheme Design Stage

At the Scheme Design Stage additional simulations were carried out to inform the design team in more detail how design changes influence the environmental performance of the building. For these studies the simulation model was passed from the ODS-Interface to the full ESP-r system, as this offered the flexibility with respect to model attribution and performance prediction analysis that was required for the study. The following aspects were identified as relevant:

- assessment of solar control options (blinds, solar obstruction elements) in the office space;
- evaluation of benefits of night time ventilation in the office space;
- assessment of solar control options (blinds, solar obstruction elements) in the atrium and
- assessment of the benefit of higher ventilation rates in the atrium.

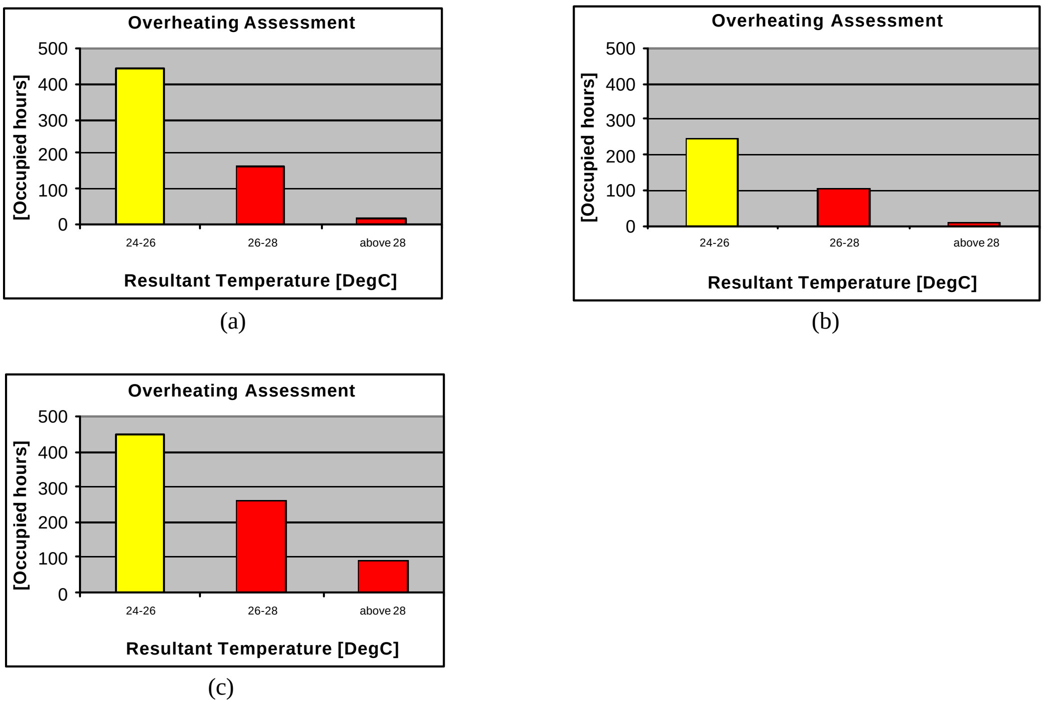


Figure 7.12: Resultant temperature in office space with different Design Options aiming to enhance the performance of the space: (a) temperature obtained in previous study (b) temperature when applying night time ventilation (c) temperature with solar obstruction elements (no night time ventilation)

In a first study an evaluation was undertaken as to whether or not solar obstruction elements (overhangs) in the office space would be as efficient as blinds and how far night time ventilation further reduces the resultant temperature during the day. Two different

Design Versions were created: one where additional night time ventilation was applied to the office space (at 4 air changes/hour during non-occupied periods) and another where solar obstruction elements (1.5 m wide) replaced the blinds (no night time ventilation). From Figure 7.12 it can be seen that the night time ventilation reduced the resultant temperature whereas replacing the blinds with the obstruction elements resulted in higher temperatures. In consequence it was decided that the night time ventilation should be applied in the building to lower day resultant temperatures, but that solar obstruction elements should be omitted. However, the night time ventilation still results in more than 100 occupied hours with resultant temperatures above 26ºC, and in consequence it was decided that the office space will be provided with artificial cooling. However, with the measures incorporated the cooling requirements were small and could potentially be met by cooling techniques such as ventilated ceiling slabs.

After assessing the performance in the office space, the focus moved to the atrium. Here the different Design Versions described in Table 7.9 were created. Figure 7.13 displays the performance predictions obtained.

Design Versions	**Ventilation Rate [ac/h]**	**Blinds**	**Solar obstruction elements**
Blinds	0.75	Yes	No
3.0 air changes/hour	3.0	No	No
Shading elements[1]	0.75	No	Yes
6.0 air changes/hour	6.0	No	No

Table 7.9: The different Design Versions created

It can be seen that the inclusion of blinds and an air change rate of 6.0 air changes per hour resulted in the greatest temperature reduction. 3.0 air changes per hour and solar obstruction elements did not provide such a good performance. However, solar obstruction elements were the preferred option by the designer because they are less costly and require no control and less maintenance. In consequence another Design Version was created where solar obstruction elements and 6.0 air changes/hour were combined. It can be seen in Figure 7.14 that this resulted in an acceptable summer performance, thus it was decided to pass the model with these parameter specifications to the Detailed Design Stage.

[1] The shading elements obstructed approximately 60% of the roof of the atrium.

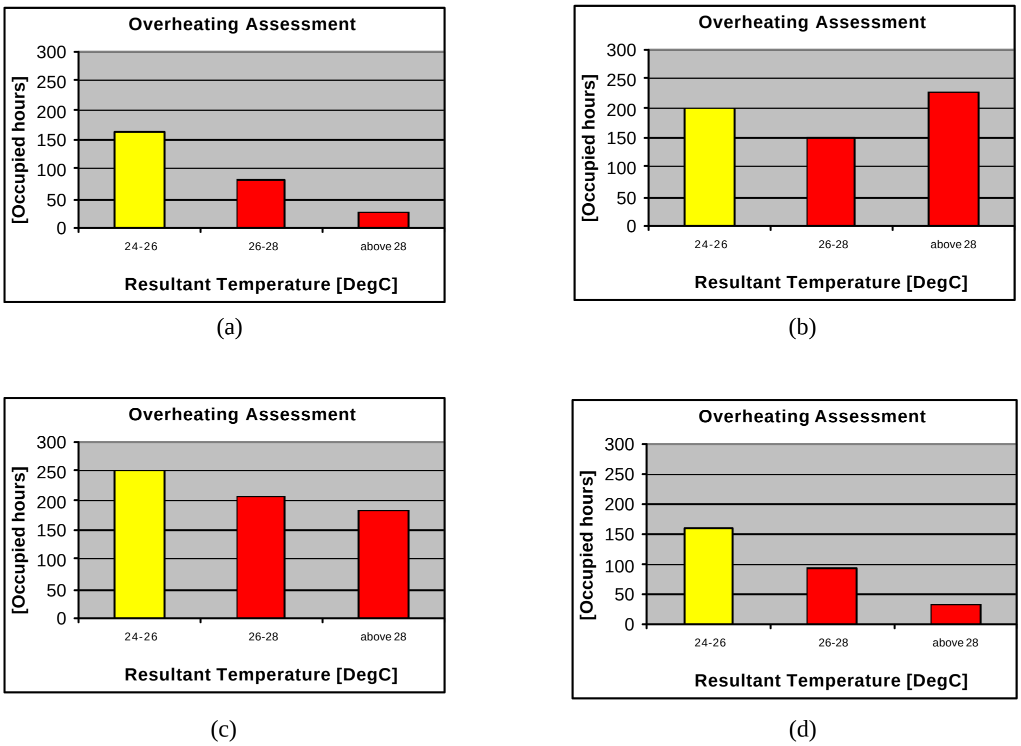


Figure 7.13: Resultant temperature in atrium with different design options aiming to enhance the performance of the space: (a) Design Version "Blinds" (b) Design Version "3.0 air changes/hour" (c) Design Version "solar obstruction elements" (d) Design Version "6.0 air changes/hour"

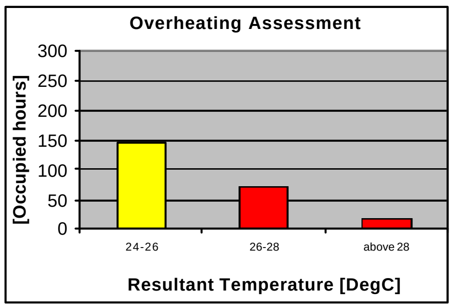


Figure 7.14: The combined application of shading elements and 6.0 air changes/hour resulted in an acceptable performance

Detailed Design Stage – data mining study

At the Detailed Design Stage the designer pays attention to issues such as the cooling system and the ventilation system of the building. The cooling requirements in the space are not excessive; therefore, cooling from ventilated floor slabs could be considered as an option. Simulation has in the past been successfully applied to evaluate the potential of these systems [Westwood et al 1997].

This case study illustrates how data mining can be used to support the designer in the planning of a natural ventilation scheme for a building. For this purpose the air flow network displayed in Figure 7.15 was included in the thermal model. It contained horizontal connections between the office zones and the atrium zones and vertical connections between the different zones specifying the atrium. For each office zone external openings were specified along the longer façade of the building and for the atrium two external openings were specified at the bottom of the shorter ends and one was specified at the top.

The simulation focused on the summer case and lasted from the 1st of May until the 30th of September. Figure 7.16 displays the air change rate in the atrium. Data mining was used to gain an initial understanding for the correlation between climatic conditions and air flow through the building.

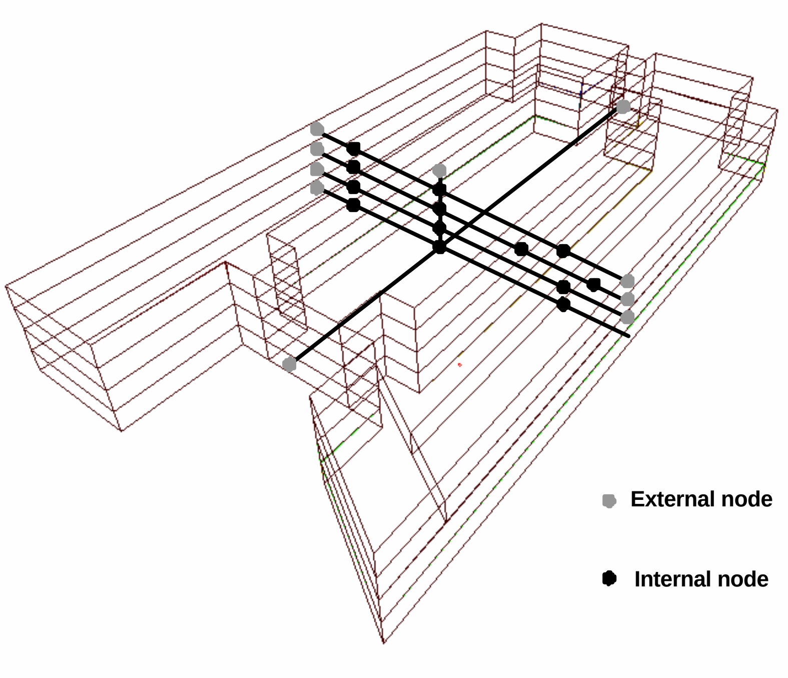


Figure 7.15: The air flow network included into the thermal model

In a first data mining run the extent to which wind speed, wind direction, ambient temperatures and direct solar radiation influence the ventilation rate of the lower space in the atrium was evaluated. Figure 7.17 displays the results. When examining the chi-square values of the different variables it can be seen that the highest correlation exists between wind speed and the air change rate in the space.

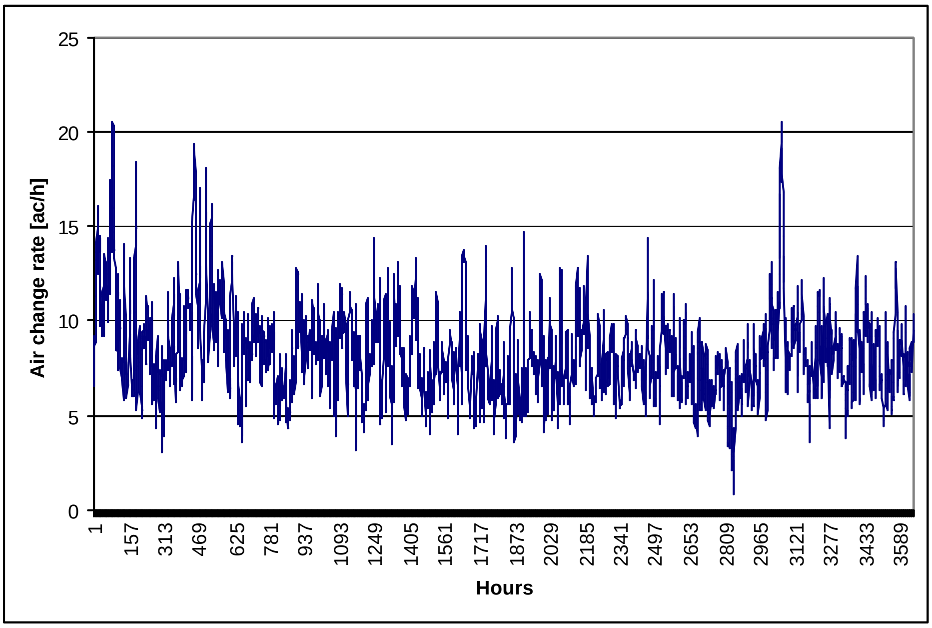


Figure 7.16: Air change rate in the lower atrium space

In a second exercise, the influence of wind speed, wind direction, ambient temperature and direct solar radiation on the air flow in the building was examined. Figure 7.18 displays the results for the cluster with minimum upward or downward flow. It can be seen that this occurs in periods with wind speed above 3 m/s. This was also confirmed by a simulation consultant [Ho 1999] who stated that she had observed that in the case of wind speeds exceeding 3 m/s, wind becomes the driving force for building ventilation and air flow switches from stack driven upward ventilation to cross ventilation. This pattern was discovered when analysing numerous CFD and air flow network simulation results.

Figure 7.19 shows another data mining analysis that underlines the finding above made by Ho. The figure displays air flow through the external opening of the south/west facing office space on the ground floor (positive data indicates air flow from the outside to the inside). It can be seen that air flow from the inside to the outside only occurs at time when the wind speed exceeds 3 m/s.

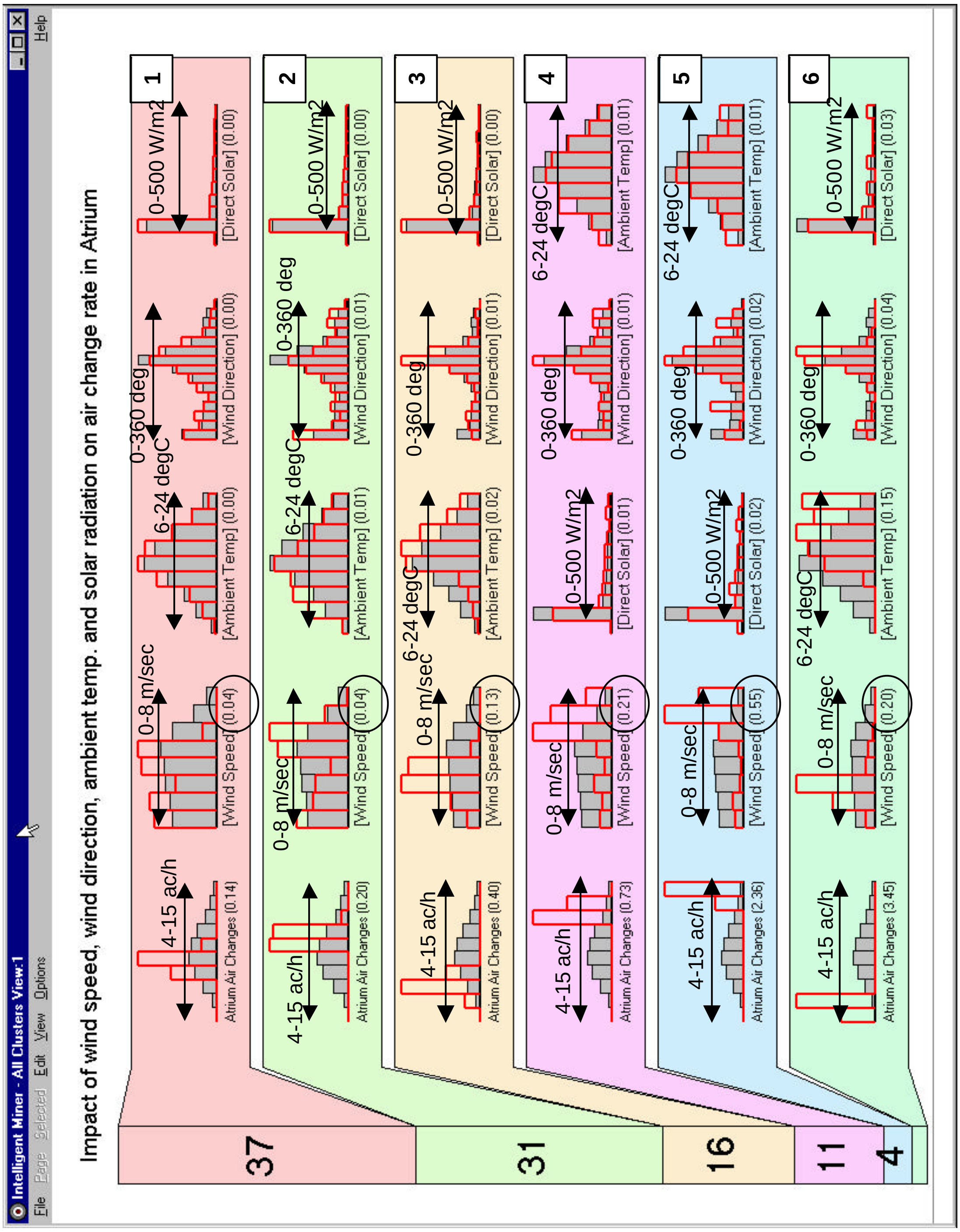


Figure 7.17: High chi-square values for wind speed in an assessment of parameters influencing the air change rate in the atrium. Note that some boundary values have been excluded from the display.

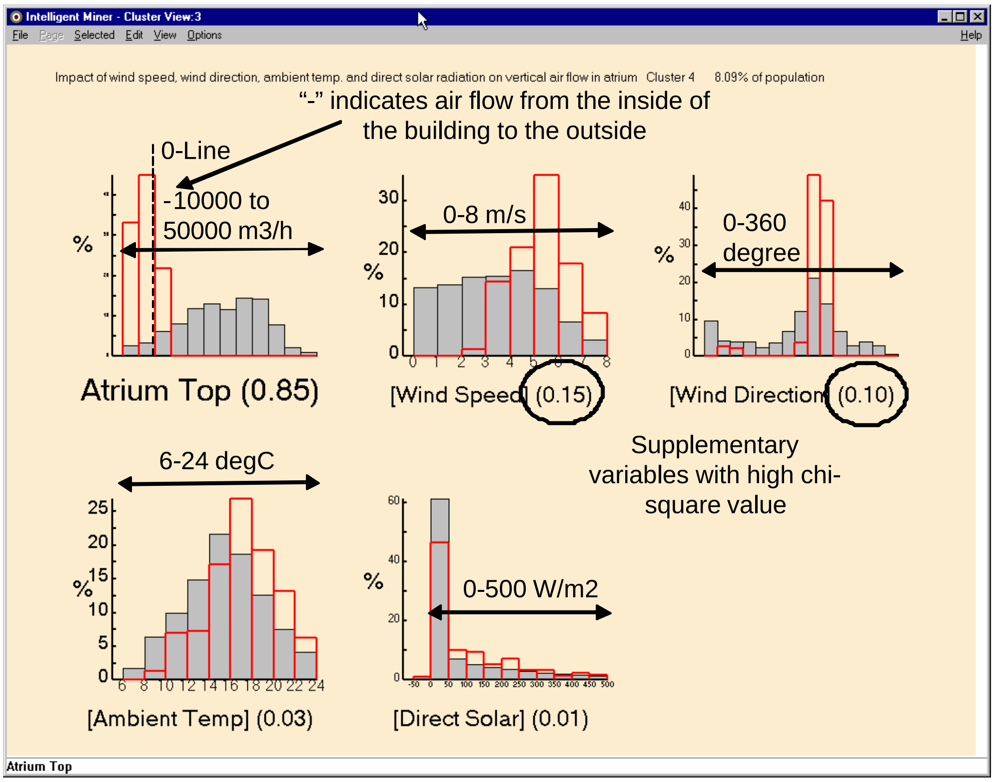


Figure 7.18: Small vertical air flow occurs with wind speed above 3 m/sec.

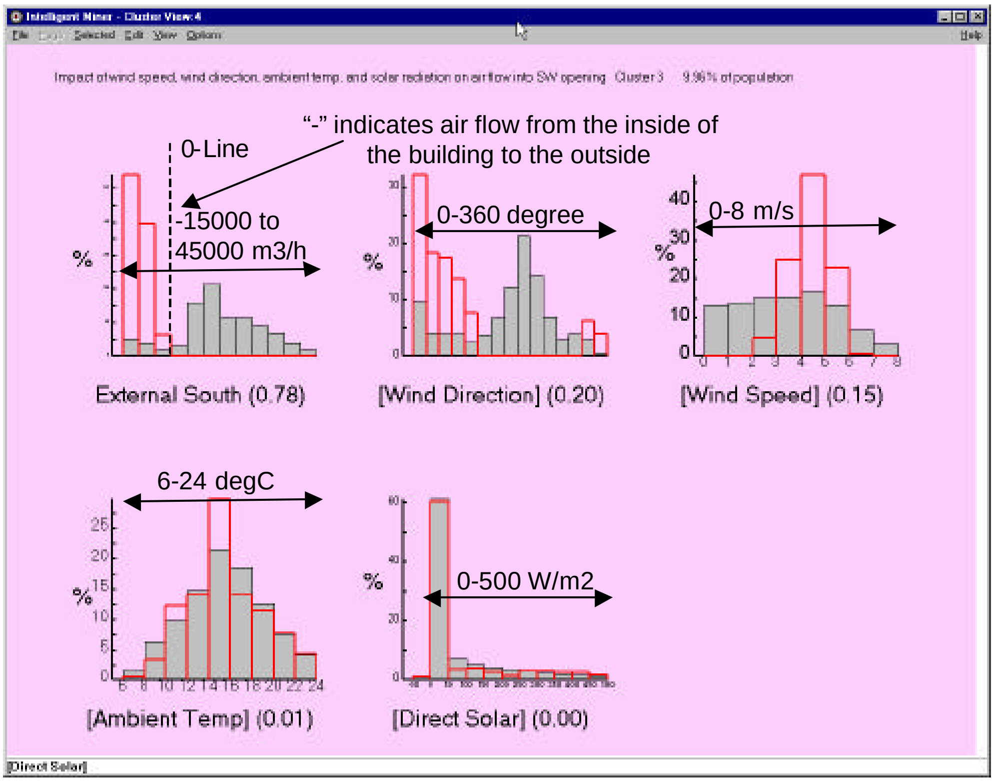


Figure 7.19: Cross ventilation occurs with wind speed above 3 m/sec.

Discussion of case study

This case study shows how simulation exercises structured towards the requirements of the building design process can support designers in their decision making. It also illustrates how the same simulation model has been passed from early to later design stages and was expanded over time.

The case study also shows the usefulness of data mining for the analysis of air flow networks, where boundary conditions constantly change and the system also has a quick response time. The analysis and visual display provided by the clustering technique can be a beneficial support tool. Apart from the studies shown, additional studies could also be carried out in order to evaluate other considerations that occur when designing an air flow network: e.g. when drafts occur through an external opening, when stack driven ventilation is strongest, what influence wind direction has on air change rates within a space when external openings do not face in every direction (as was the case with this air flow network), etc.

7.3 Surveys of practitioners

7.3.1 Introduction

The application of simulation at the Outline Design Stage has the implication that non-simulation experts create simulation models and architects utilise a tool that previously found only limited application at this design stage. The following section describes a survey that was carried out to identify how the designers responded to using the software to aid their design.

7.3.2 Survey types

Surveys can be carried out with different intentions. Robson [1993] identified two different extremes: at one end the scientific approach, where the researcher first deduces a hypothesis and then tests this hypothesis with a survey; the other extreme is the interpretative approach, where theory and concepts arise from the enquiry that is carried out. Later Robson points out that especially in small-scale real world investigations (the type of research carried out as part of this work) both approaches tend to present difficulties to the researcher. For the scientific approach there is often not sufficient background knowledge to base a theory on, and a free range, interpretative analysis is often influenced by the fact that the researcher already has an idea of the direction in which the result will point. He then proposes a marriage of the two approaches where the researcher might already have an opinion about potential findings but is still open to unexpected discoveries. This approach was applied in the survey described here.

Dyer [1993] distinguishes four different survey types:

- The ***one shot design*** in which the data are collected from a single sample drawn from the population of interest.
- The ***before-after design***, where the samples are collected from the members of a single group on two distinct occasions.
- The ***two group controlled comparison design***, where data are collected from two separate samples, where each sample has received a different form of treatment before the data collection.
- The ***two-group before-after design*** which combines both of preceding ones.

In this research the users of the ODS-Interface were interviewed based on the one shot design method. A two group controlled comparison design would also have been interesting, with one group using a advanced dynamic building simulation program at early design stages, and another group the ODS-Interface developed especially for this purpose, but because of the significant implications of such a study for any design team it was not possible to create a research environment in which such a study could have been conducted.

7.3.3 Data collection

Every survey requires data collection, and again there are different approaches that can be used – observation, interviewing and questionnaires are the approaches mainly used, and for interviews one also distinguishes between the structured interview and the unstructured, free-range interview. This research was carried out in the form of structured interviews based on a list of question that were predefined. The questions included closed questions where the range of possible answers was pre-determined and open ended questions which did not limit the nature of response.

Altogether 12 people were interviewed as part of the research. It was regarded as important that all participants had used simulation on live projects rather than only being introduced to the tool 'in theory'. At the beginning of the interview, every interviewee was assured that answers would be kept confidential because only then it could be ensured that observations recorded were based on experience and not assumptions or misinterpretations by the designers (based on a 'theoretical introduction' to simulation). To avoid group pressure on the interviewees every person was interviewed separately. The interviews were structured with different phases to ease the data collection process: introduction, warm up, main body of questions, cool off, closure. Notes were taken during the interview, but properly recorded immediately after. Before the interview session the structure of the questionnaires was tested in a dry run with an interviewee well known to the interviewer.

7.4 Observations from survey of designers

The survey covered two groups of designers: 4 users of the ODS-Interface and 8 design team members who had used performance predictions obtained from simulation as part of their decision-making[1]. Appendix 4 list the contents of the questionnaire on which the interviews was based.

7.4.1 Users of the ODS-Interface

Simulation exercise in general

The users of the ODS-Interface stated that they found a simulation exercise 'not difficult' or 'slightly difficult'. None of the users found it difficult or very difficult. Another observation was that difficulties were not related to the attribution of the simulation model with the ODS-Interface but to the definition of the model geometry (see sections below). This shows that the ODS-Interface can be operated by non-simulation experts to undertake simulation studies at the Outline Design Stage.

Geometry definition

One user found the definition of the CAD-geometry difficult; the others found it 'slightly difficult' (none of the users found it 'very difficult' or 'not difficult'). The user who found the geometry definition difficult had no previous experience of creating a drawing in 3D. All of the users said that the main difficulty when specifying a model geometry is the fact that the drawing has to be 100% accurate. This contradicts the normal use of 3D in CAD, where the aim is to produce 'pretty pictures' and drawing inaccuracies are acceptable as long as they do not impact on the visual quality of the drawing. One user emphasised that some of the aspects required when drawing a model geometry can limit the usability of the CAD tool (e.g. sub-division of surfaces after extrusion from 2D to 3D). Another example given was the fact that vertices that had been included into subdivided surfaces to properly bind the zone were not moved when the surface was moved.

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[1] At the time when this publication was finalised the number of designers who had used the ODS-Interface on projects had increased to 10 and a larger number of designers had also used performance predictions obtained from simulation as part of their decision making. It was generally concluded by the author that patterns described in the following were confirmed when a wider group of people used the tool.

Despite difficulties, all users found it 'important' or 'very important' to be able to use the practice's usual CAD tool for the specification of the model geometry. Familiarity with the user functions of the CAD tool and fast data definition (because existing drawings could be used as a template) were rated as important. One user said that a commercial simulation package he had tested had CAD functions that did not follow industry standards and said that he believed non-simulation experts would not use simulation if it was not linked to industry standards.

Use of ODS-Interface

All the users of the ODS-Interface[1] found the operation of the program not difficult. They all saw the guided input procedure and the in-built structure of Design Options and Design Versions as important for this ease-of-use. One user emphasised that the latter also ensures that data is not lost because a user alters a simulation model by continuously changing the same model. In a sense that shows that with the ODS-Interface an (arguably minimal) "undo" function is provided, which Hand [1998] stated to be missing with advanced simulation programs.

The rating of the support databases varied. Two users found the support databases restricting and would prefer to be able to also specify data themselves, the two others stated that they preferred the population of the databases to be carried out by others because they lack the background knowledge to carry out the task. The users who preferred to be able to specify databases themselves gave increased control and flexibility as reasons for their choice. Still, they also recognised that this would require additional training to enable them to specify appropriate data.

It was interesting to the author that some users expressed interest in populating databases themselves. This shows that they want to take an active role in enhancing the tool and improving the quality of performance predictions. However, this would have QA implications because it would need to be ensured that the users specify correct data. It could also slow down the model creation process and hence interfere with the important feature of the ODS-Interface of producing performance predictions quickly. Future deployment of the

[1] The ODS-Interface was mostly operated by younger architects who were in their normal working life mainly involved in detailed, technical design tasks and not so much in strategic design decisions. Carrying out simulation exercises provided them however with an opportunity to be involved in these higher level design considerations of the building design and also enabled them to deal with energy and environmental design issues. Both aspects were observed by the author as a motivation to become involved in simulation exercises.

ODS-Interface will have to give indications of appropriate ways to populate the support databases.

Difficulties with simulation

When asked about other difficulties with the use of simulation the following issues were raised:

- The fact that a zoning strategy for a simulation model varies with both building type and simulation aim was perceived by two users as confusing. They stated that they would have preferred general rules that apply to any simulation exercise (e.g. always specify a 6 metre perimeter zone for any simulation model).
- One user who was involved with the collection of data for the support databases found dealing with related issues fairly difficult. It should however be emphasised that this was also a user who had previously stated that he would prefer to be able to populate support databases himself. This shows that the task was perceived by him as generally accomplishable (which was however not the case for all users).

7.4.2 Designers using performance predictions from simulation

The survey covered 8 designers, of which 7 were architects and one was a building services engineer working in the architecture company. In the following, the term 'designer' will be used if a statement relates to both the building services engineer and the architects.

Previous ways of addressing energy and environmental issues

All architects interviewed were previously aware of the existence of simulation programs. Two had directly commissioned simulation exercises. Two others were involved in simulation exercises when working with consultants (building services engineers). The architects had also addressed energy and environmental issues; they clarified this with statement such as 'an understanding of environmentally friendly design concepts', 'applying working procedures that consider energy and environmental issues, e.g. considering the sun path on the site', 'ensuring compliance with building regulations' and 'general dialogue with building services engineers'.

Reasons for limited use of simulation

When asked about reasons for the limited use of simulation within the architectural design process several reasons were given. Most designers mentioned the fact that architects are 'visual people' and simulation can be seen as too abstract. However, two designers stressed the fact that once the situation exists whereby a simulation exercise can be carried out with a tool suitable for architects they would be prepared to apply the tool (this related to both model creation and performance analysis). Both designers also stated that they believe this was achieved with the ODS-Interface. Two designers also mentioned that many designers believe that compliance with building regulations would ensure good energy and environmental performance; one architect said that designers might not want to be 'caught out' with a poor design and do not want to know during the design phase how the building is likely to perform ('design to walk away', as he phrased it).

Performance prediction presentation

One architect stated that the presentation of the data in a simple graphical form is sufficient. However, most of the other architects said that they would prefer the performance predictions to be presented with more supporting information. One example given was explanations of how the occupants will perceive temperature distribution in a space in terms of comfort. Another architect also stated the risk of providing just the performance predictions to the client without interpretation. He saw a risk that the client will either not make the effort to try and understand the results or misinterpret them.

Quality assurance (QA) and liability

All designers recognised the importance of QA. Three architects stated that despite the fact that architects carry out the simulation exercise the responsibility for the energy and environmental performance of a building should remain with the building services engineer – the application of simulation by architects should be only to inform them in their decision making. It should be considered whether building services engineers are prepared to take this additional responsibility.

Role of simulation in bridging the gap between architects and building services engineers

Without exception, all designers recognised the role of simulation in bridging the gap between architects and building services engineers. The architects stated that the use of simulation gives them a better understanding of building services issues. Two architects also stated that it would increase their 'authority' towards building services engineers, having experienced in the past that building services engineers were not prepared to evaluate a building design on the basis that the design had not been sufficiently developed. The building services engineer, however, stressed that he sees a movement towards more teamwork in the design process, which he had missed in the past. This can be supported with the statement of one architect that historically some architects preferred to involve a building services engineer at late design stages. Despite differing views on this issue there seems to be a general consensus that architects and building services engineers should work more closely and that simulation can help bring the parties together.

Catalysts for the integration of building simulation into the building design process

All designers were convinced or very convinced that PFI-projects(see section 1.6.4 for PFI) were an important vehicle for the integration of simulation into the architectural design process since with these design projects the investor paying for the construction of the building also pays for the life cycle cost of the building (energy requirements, cleaning, repair, etc.). This makes the life cycle cost of a building a more important design consideration and PFI clients have started to develop an interest in this field.

One architect mentioned the fact the company in which the ODS-Interface was tested had a history in the use of an object orientated CAD system and has in consequence a tradition in design support from the CAD system.

Advantages of in-house application of simulation

Most architects stated that external consultants would not respond in the required time scale. Commonly expressed views were also that the application of simulation by architects enhances their understanding of energy and environmental issues. One architect stressed that in order to successfully incorporate simulation into the design process it is necessary to have the facilities in-house, e.g. as a common basis for designers to discuss project work.

Future deployment of simulation in the construction industry

When asked about their view on the future deployment of simulation in the construction industry all except one designers stated that they were convinced or very convinced that simulation will at some point find a standard application as an EEDDSS. Time predictions were however not consistent and varied from 5 years because the tool is a necessity to 'a long time' because the construction industry is sluggish.

The building services engineer also emphasised the increased demand on the energy and environmental performance of a building design by the new Building Regulations. This means that the architects will have to take responsibility for design aspects that are currently dealt with by building services engineers. This could potentially support the application of building simulation by architects even at later building design stages.

Problems with simulation

Two architects stated that they would prefer more detail in the modelling exercise. One gave the example of solar control at the façade of a hospital building which would affect rooms differently because they have very different usage functions and hence varying occupancy densities, internal heat gains, etc. The architect said that this should be reflected in the model. It is interesting that the same architect also stated that a simulation tool should provide responses to a design evaluation within 30 minutes (including QA). However, he was also generally very supportive to the idea of using simulation in the design process. The statement points out that the designer had recognised the level of detail with which simulation carries out an evaluation, but that he also sees requirements for further developments to fully integrate it into the design process.

7.4.3 General comments in the survey

The survey was carried out in the early days of the application of advanced simulation by architects. As a consequence of this, for some issues, final conclusions could not be drawn. However, in general the survey showed that the research undertaken had enabled the application of building simulation at an early building design stage.

7.5 Feedback from building simulation consultant about data mining

Two consultants running building simulation consultancy companies (Catherine Simpson of Building Simulation Ltd and Mike Whalley of Building Performance Ltd) reviewed a report with the data mining exercises described in this thesis. One of them had also provided the model that formed the basis of the case study described in chapter 5; the other was familiar with the exercise.

Both saw data mining as a useful tool for the analysis of simulation exercises (one of them naming it an invaluable contribution to the building simulation industry). They stressed that the tool will save the experienced modeller a significant amount of time because it would remove the need for much manual analysis and allow efforts to be focused on solving building performance problems rather than their identification.

One consultant made clear that for inexperienced users data mining would be a useful tool that should shorten the analysis learning curve and enable them to gain experience more quickly. However, she also stated that the novice would still need to know what questions to ask and what variables to include in the analysis process. Although this can be seen as a disadvantage of design assistant DDSS it was said in section 5.2.2 that this approach has the significant benefit that it gives the designer insight into the behaviour of a design problem and also helps build up knowledge which can be utilised in later design projects.

Data mining was seen as a tool which provides the opportunity for a wider investigation, hence obtaining more information from a simulation exercise. Both consultants also emphasised that in many cases a ‘commercial’ approach for a simulation study is to identify problems with the building performance – investigating the problem is not feasible because it is too time consuming. If data mining became standard practice this situation could change.

Despite the positive feedback regarding the use of data mining for the analysis of performance predictions obtained from a simulation exercise both consultants also stressed that additional simulation runs may need to be performed to test conclusions drawn from the data mining study – the tool points the user in the right direction but knowledge obtained might not be conclusive.

After being introduced to the tool both building simulation consultants expressed interest in using data mining on their projects and have expressed interest in using data mining analysis for the examination of simulation exercises they are working on.

7.6 Closing remarks

The first part of this chapter described three case studies. Two of them showed how the application of building simulation at early building design stages can support the decision making of the building designer. The third one showed how simulation can be applied in a structured way throughout the building design process.

The second part of the chapter described findings from a survey of designers who were involved in simulation exercises. The survey showed that the ODS-Interface had enabled non-simulation experts to create a simulation model and also highlighted the importance of a performance analysis in a manner suitable for architects. Both architects and the building services engineer saw simulation as a tool that can help bridge the gap between the two professions, but the issue of responsibility for the energy and environmental performance of a building arose. Hands-on experience was the most quoted benefit of the application of simulation by architects.

The final section summarised feedback given by two building simulation consultants about the applicability of data mining for the analysis for simulation models. Both indicated that the tool will speed up the analysis process and support the designer in solving performance problems but will also help inexperienced users to shorten their learning curve. Both now use data mining analysis on their simulation projects.

References

BRESCU, "Energy Use in Offices", published within the "Energy Efficiency Best Practice Programme" as part of the UK Government's Energy Efficiency Program for the Built Environment, 2000.

CIBSE (Chartered Institution of Building Services Engineers), "CIBSE Guide A - Environmental Design", 1998.

DTLR (Department of Transport, Local Government, Regions), "The Building Regulations 2000, Part L2", 2002.

Dyer C, "Beginning Research in Psychology – A Practical Guide to Research Methods and Statistics", Blackwell Publishers, 1993.

Hand J W, "Removing Barriers to the Use of Simulation in the Building Design Professions", PhD Thesis University of Strathclyde, 1998.

Robson C, "Real World Research", Blackwell Publishers, 1993.

Sharples P, Corporate Maintenance Manager of Prison Blakenhurst, Personal Communication, 2002.

Westwood R, Benstead R, Edwards, "Advanced Fabric Thermal Storage III: Theoretical Analysis and Whole-building Simulation", Building Services Engineering Research and Technology, Vol. 18, CIBSE, pp 17-24, 1997.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Introduction

Early in this thesis it was indicated that the complex and multi-objective contemporary building design process has advanced the development and use of design decision support systems (DDSS). By not using such tools during the design process can result in poor design quality because the designer is unaware of the performance implications of design choices. It was also observed that energy and environmental considerations are currently given only limited attention in the contemporary building design process, but reasons were also identified why this situation might change in the near future. A review of different energy and environmental DDSS (EEDDSS) then identified dynamic building simulation as the most appropriate tool to address these design considerations. It was, however, also stated that simulation does not find regular application in the building design process, partly because the programs have not been developed to a degree required by building designers. Although the tools now have impressive capabilities in terms of the simulation tasks that they can carry out, a number of barriers remain which restrict the use of such tools by designers: the relative lack of regard for the importance of energy efficiency; the lack of a structure for the inclusion of simulation in the design process; complex user functionalities; limited performance prediction analysis and issues connected with uncertainty and validation. This resulted in the development of the research aim of moving dynamic building simulation into a DDSS that is better integrated into the building design process, in order to enable designers to better understand implications of design decisions on the energy and environmental performance of a building, particularly at the early design stages. This should lead to more informed decision making.

The steps necessary to achieve the research aim were specified with the following objectives.

- Development of a methodology for the use of simulation within and throughout the design process.
- Specification and development of a tool that enables non-simulation experts to create a detailed simulation model at early building design stages.
- Specification of concepts and techniques for appropriate performance prediction analysis.

- Implementing and monitoring of the use of simulation at an early building design stage in an architectural design practice.

Research into the methodology for the use of simulation in the building design process was carried out for the three simulation types that had been identified as most relevant for the application in the building design process (thermal, air flow and lighting simulation). With regard to the other objectives, the focus was on thermal and air flow simulation. The research into the simulation supported design process was carried out in a close, long term working relation with designers in an architecture company. This had benefits such as a detailed, focused study of how to best incorporate simulation into the design process and the option to test developed software more thoroughly.

8.2 Towards the integration of building simulation into the building design process

8.2.1 Simulation supported design process (SSDP)

Chapter 2 of this thesis described how efforts over the last decades have resulted in the development of simulation tools with advanced capabilities. It was however, stated that currently guidance was missing as to what kind of simulation exercise should be carried out at different building design stages. Making such a decision without support and/or advice can be difficult, especially for non-simulation experts. In order to better integrate simulation into the building design process it was hence found necessary to develop a concept of how to utilise simulation at the various building design stages. This was achieved by developing a specification for a simulation supported design process (SSDP).

The SSDP was developed on the basis of the RIBA (Royal Institute of British Architects) Design Plan of Work, which is well recognised within the building industry. From the twelve design stages listed in the RIBA document three were identified as relevant for the SSDP: (1) Outline Design Stage, (2) Scheme Design Stage and (3) Detailed Design Stage (see section 3.2). All three were described in the thesis along with a discussion of how building simulation can support decision making in the different phases. It was found that the application of simulation during the different design stages would differ, with quick evaluations of fundamental design decisions at early design stages (often carried out by architects) and detailed technical studies at late design stages, mainly performed by engineers. This had to be taken into consideration in later periods of the research which focused on the development of tools and techniques to integrate the SSDP into the building design process. It was decided that the SSDP should conform to the following specifications: it should allow the evaluation of all common design parameters of interest to the designer, be flexible for future extensions and provide user interfaces that will be accepted by designers but which maintain good levels of accuracy.

The implementation concept for the SSDP which was chosen in response to the specification was to use the same advanced simulation engine (ESP-r [ESRU 2002]), throughout the design process, but with interfaces and performance analysis methods tailored towards the requirements of the different design phases. The ESP-r system offers an extensive number of simulation capabilities; the software has also been developed in a manner that allows its extension with additional simulation functions and it has been validated in several exercises.

It was highlighted that some publications propose the use of entirely different simulation tools at the various design stages. However, this approach was discarded in favour of the advantages of the approach selected for the SSDP. One of these advantages was the fact that performance predictions are based on the same simulation engine, hence performance prediction differences will only be caused by variations in the simulation models and not by the use of different simulation engines. It was also made clear that any future enhancements of the simulation engine would benefit all design parties. Another advantage was the fact that by using the latter approach, simulation models can be exchanged between different design parties. By doing so, simulation can play an important role in bridging the gap between architects and building services engineers, encouraging a design process where architects and engineers design jointly and benefit from each others knowledge, therefore improving the decision making of the designers and thus the quality of the final building design. This benefit was also underlined in a survey carried out among designers using simulation on design projects who stated that they see it as a useful tool to bridge this gap. In the case of the architecture company where the ODS-Interface was implemented the use of the software resulted in the initiation of close working collaborations with three building services engineering companies.

The development of the SSDP also included research into design parameters to be evaluated at the various design stages. Design parameters that were included were selected under the following conditions: (1) parameters that the designer wishes to evaluate; (2) parameters with important implications that the designer should be aware of, and (3) parameters that are cost effective and that are established in the built environment. The specifications were made with the aim of making the SSDP applicable in a conventional design situation. The outcome of the research was also compared with two other design published parameter classifications and an acceptable agreement was observed.

8.2.2 Simulation model creation at the Outline Design Stage

It is believed that the integration of simulation into the design process requires the development of simulation tools that are adapted to the design process and not vice versa (see section 2.5.2). However, user functions of advanced simulation programs are too complex for a non-simulation expert and non-frequent user. In response to these observations, research was carried out into an ODS-Interface that enables architects to create detailed simulation models at the Outline Design Stage. This research was covered in chapter 4 of the thesis.

The ODS-Interface utilises a Database Management System (DBMS) in order to support the various data processing functions that need to be carried out within an advanced simulation program. The use of query functions as well as an increased transparency of the data structure were identified as valuable benefits from the use of a DBMS. The data model that was developed for the ODS-Interface had a clear separation of Design Option data (geometry related data) and Design Version data (attribution data for a geometry) as well as Support Databases. A comparison with other data models concluded that the ODS-Interface data model was mainly developed for the support of the application of simulation at early building design stages.

The ODS-Interface utilises the CAD tool currently used in the test bed practice for the specification of the simulation model geometry, allowing the application of advanced user functions and visual displays that such tools provide. In addition, it enables designers to use existing drawings as a template for the specification of simulation model geometries, reducing time requirements to create a model and lessening the risk of input errors. The CAD drawing is also used by the ODS-Interface to indicate zones or surfaces during the model attribution process. It was concluded that all this links simulation closely to a standard design tool and hence embodies it into the standard work of architects. The importance of being able to use CAD in conjunction with building simulation was later underlined by architects who used the ODS-Interface on design projects and confirmed the above described benefits as very relevant.

The guided input procedure which assists the designer in the specification of a simulation model is another important element of the ODS-Interface. The user is guided through the various steps involved in the creation of a model and hence needs not be concerned about tasks that need to be carried out when creating a model or how to navigate through the software to accomplish them. Another element of the ODS-Interface is the Support Databases which speed up the model creation process and reduce the risk of input errors because many data items are automatically attributed by the software rather than manually by the user (e.g. operational or control data is not specified by the user but underlies a zone function type the user selects). Architects who used the program rated both the guided input procedure and the Support Databases as important elements of the ODS-Interface. Some designers did express interest in an active involvement in the population of the Support Databases - others stated they would prefer this task to be carried out by a simulation expert. It was concluded that a longer-term application of the ODS-Interface would be required to develop appropriate means to populate the databases.

8.2.3 Analysis of performance prediction

Chapter 5 described research into the analysis of performance predictions. Firstly it discussed energy flows and parameter removal as *causal analysis techniques* for discovering reasons behind a certain building performance. It was found that both approaches had advantages but also limitations. It was concluded that for early design stage applications energy flow analysis could provide useful information for the designer. *Design guiding analysis techniques* were then introduced and discussed. These deal with the investigation of different design options that can be applied to resolve a performance problem. It was concluded that the *design assistant* and the *design automation philosophy* define outer boundaries of this analysis approach. The design assistant approach was favoured because in addition to the development of a design solution with a good energy and environmental performance it also provided the designer with insight into the building behaviour. During the process of creating different simulation models using the method the designer is able to built up knowledge regarding what design parameters affect the building performance, and this information can be useful when putting it into the overall design decision making process for a building (e.g. smaller windows are crucial to summer comfort and should be maintained in the building design). In addition, such a deeper understanding help the designer build up knowledge which can be utilised in future design projects.

The concept of an expanded Integrated Performance View (IPV) for the Outline Design Stage was introduced. It includes benchmark figures for a building type, whole building energy consumption figures and explanations of performance predictions obtained, which can be applied in combination with an energy flow analysis. Architects in the test bed company who later used simulation on projects emphasised the need to be provided with such additional information and suggested additional information option.

Data mining was then introduced as a novel method for the analysis of performance predictions obtained from a simulation exercise. The aim was to enhance at the Detailed Design Stage the analysis of large data sets that are obtained from simulations covering longer evaluation periods. In difference to the expanded IPV data mining is seen as a tool to allow designers to interactively explore these data sets – it does not aim to be tool to produce performance prediction displays to be presented to clients.

Different data mining philosophies and techniques were explored, resulting in the identification of three different techniques potentially appropriate for the use in conjunction with building simulation: association mining, clustering and classification mining. The functionalities of all three tools were illustrated and further evaluated with a simple case study. From this exercise it was concluded that clustering is most suitable for the analysis of performance predictions obtained from a simulation exercise.

In a cluster analysis the data is grouped with the aim of placing data instances in segments (clusters) in a way that maximises the similarity between instances of one segment and minimises the similarity between the instances of different segments. With the clustering software evaluated it was possible for the designer to specify for this grouping active and supplementary variables. The clusters created are based on the active variables, but by determining the chi-square value possible correlations between active and supplementary variables can also be identified. This gives an understanding of how far supplementary variables influence the behaviour of active variables. It was stressed, however, that the relevance of any identified correlation would still need to be verified. A final advantage of cluster analysis was the fact that it uses a comprehensive data display in a format the designer is already familiar with (frequency binning), so despite the fact that the tool introduces additional elements to the analysis process it is not too removed from a conventional analysis process. This was found to be one of the disadvantages of association mining and classification mining.

Two more complex case studies then illustrated how clustering can be used in conjunction with simulation. A general discussion of data mining stated that the tool does not automatically determine all the knowledge that is embedded in a large dataset but follows the design assistant approach with the designer having the control over the evaluation process and decision making.

It was also highlighted that a major barrier for the application of data mining in conjunction with simulation is the tedious data transfer between the simulation software and data mining tool (although once this task has been accomplished data mining is a tool that can be operated quickly and interactively). However, an increased application of data mining could free up development resources and increase its usefulness in the building design process.

8.2.4 The implementation of simulation

Chapter 6 first illustrated how research contributions described in previous chapters can be used to provide the integral application of building simulation throughout the building design process. It then discussed practical implication issues with a special focus on the use of simulation by architects. Differences were observed for the model geometry definition and attribution as well as database population at early and late building design stages. In terms of QA it was emphasised that only the combined application of verification and validation can ensure decision making that is based on appropriate performance predictions. It was then shown how validation and verification are supported by a documentation of the model, management procedures and training.

8.2.5 Application, implementation and feedback from designers

Chapter 7 demonstrated how the developments were brought together to facilitate the key objective of this thesis: the integration of simulation into the building design process. It firstly described three different case studies. The first two showed for a prison and an office building how the application of simulation can enhance the understanding by the designer of energy and environmental implications of early stage design decisions and can provide information that would not have been available without the application of simulation. In the case of the prison study this was due to the fact that easy to use computerised EEDDSS normally do not provide the option to evaluate the energy and environmental performance of such a building type. For the office, simulation showed that building behaviour differed from that suggested by best practice advice. It was also shown that design concepts promoted as improving energy performance within the building regulations do not always reduce the building energy consumption.

The third case study illustrated the SSDP – a structured application of the same simulation tool throughout the design process, with simulation exercises tailored towards the requirements of the various building design stages. It also illustrated how the simulation model could be passed from one simulation tool to another during the design process and during the process, could be refined over time. The case study also showed the usefulness of data mining for the analysis of air flow networks, where boundary conditions constantly change and the system has a quick response time to these changes.

In the second part of the chapter findings from a survey of designers who were involved in the use of simulation as part of the early stage architectural design process were discussed. It was concluded that the development of the ODS-Interface had resulted in a tool that enables non-simulation experts to carry out a simulation exercise as part of a design project at the Outline Design Stage. Interestingly, the users of the ODS-Interface had no problems in operating the program but found the definition of the simulation model with the CAD tool slightly more challenging. All of the users said that the main difficulty when specifying model geometry is the fact that the drawing has to be 100% accurate, which contradicts the normal concept of a 3D drawing where the model only needs to be accurate enough to give a good visual appearance. All users of the ODS-Interface highlighted the importance of being able to use a CAD tool.

QA was recognised by all designers as an important issue when applying simulation at early building design states. Most architects stated that despite the fact that architects carry out the simulation exercise, the responsibility for the accuracy of performance predictions obtained from a simulation exercise as well as the energy and environmental performance of a building should remain with the building services engineer. It was concluded that the future application of simulation will need to show to what extent building services engineers would be willing to agree to such an arrangement.

When asked for their opinion about benefits when architects use simulation in-house rather than commissioning external consultants, a commonly expressed view was that architects get hands-on experience with energy and environmental design issues. This acknowledges benefits from the fact that the ODS-Interface follows the design assistant philosophy.

With respect to the applicability of data mining for the analysis of simulation models two building simulation consultants stressed that the tool speeds up the analysis process and enables the designer to focus on solving performance problems rather than their identification. This could move simulation away from an often applied ‘commercial’ approach where the main objective is the identification of performance problems. In addition they both agreed that data mining could also help inexperienced users to shorten their learning curve. Both consultants have expressed interest in using data mining analysis for their simulation projects.

8.2.6 Comparison with other research to integrate simulation into design process

During the research two other initiatives were identified that aim to integrate building simulation into the building design process: the Scottish Energy Systems Group (SESG) and "Solaroptimierte Gebäude mit minimialem Energiebedarf" (Solar optimised buildings with minimum energy consumption) in Germany.

The former was identified as potentially more appropriate to achieve recognition among designers regarding the value simulation can bring to the building design process because it presents simulation as a design tool that can make contributions to any type of design project, whereas the German project relates simulation specifically to highly energy efficient building design. In addition the SESG also tries to utilise experience gained from its work with general practitioners for the enhancement of simulation tools.

The research described in this thesis applied a similar practice-orientated approach as the SESG. With respect to the development of the SSDP and simulation capabilities for the Outline Design Stage, the author worked closely and over a long period with architects, allowing the development of concepts and tools as well as their implementation and gathering of feedback in a more detailed manner than would be possible with short term working relations as in the SESG project.

8.3 New knowledge

The following lists the main new knowledge generated during the research:

- A clear exposition of how simulation should fit into the building design process.
- The implementation and testing, through case studies, of the structured approach within a design practice, particularly focused on the early design stage.
- The development of an interface that facilitates the use of an advanced simulation program by non-experts at an early building design stage, linking to state-of-the-art CAD and DBMS software.
- The evaluation of data mining as a novel concept for the analysis of building performance prediction.
- Discussion of practical aspects regarding the application of simulation at an early building design stage by architects.
- Feedback from architects about the in-house application of simulation at an early building design stage within an architecture practice as well as from engineers about the potential use of data mining in conjunction with simulation.

- Case studies that show the relevance of applying simulation (a) at an early building design stage and (b) in a structured manner throughout the building design process.

The main contribution is in the eyes of the author the fact that the research described in this thesis was carried out in close collaboration with practitioners.

8.4 Future work

The research described in this thesis has provided the platform for future research for the further integration of simulation into the building design process. Although the work documented in this thesis represents a contribution towards this ultimate aim additional work remains, some of which is outlined in the following.

8.4.1 Test of simulation methodology in other design practices

The SSDP described in chapter 3 is based on research within one architecture company. Advantages of such a research environment were described earlier (section 1.7). However, the concept should ideally also be tested in other design practices. This comparison could happen on a national level, but also on an international basis, e.g. in other European countries. This would reveal what aspects influence the way simulation would have to be applied in the building design process. Possible issues could range from differences in boundary conditions that influence the design (e.g. climatic conditions where the building will be located could affect some of the parameters investigated) to expectations of clients from a building design (e.g. maximum construction cost, expected performance from the building). Another relevant point is that it could be, for example, considerably more complicated to encourage designers to use simulation if they are not familiar with the use of CAD systems.

8.4.2 Internet or Intranet based simulation software

The ODS-Interface developed as part of this research utilises a DBMS. This makes it easier to integrate simulation into Internet- or Intranet based software tools. In terms of system configuration different setups are possible for such a development, ranging from all the functions being carried out on a central server to certain actions being taken by locally installed software components.

Data access in these tools could also be controlled on different levels. One option would be that a user can attribute predefined geometries. Simulation exercises would, however, be more flexible if it was also possible for the user to specify geometries. Other intermediate solutions would also be possible.

With the current developments in the working environment of building designers it is likely that Internet or Intranet based applications will at some point be necessary to utilise simulation programs in the building design process. Internet and Intranet are becoming more used to connect offices located in different parts of the country and to enable staff to work from home [Mahdavi et al 1999]. In addition it could also link the users of a simulation program to the operator of the tool, hence enhancing support options that can be provided to the user.

8.4.3 Software tool for the Scheme Design Stage

Currently the SSDP utilises the fully functional ESP-r interface and the ESP-r analysis tool at the Scheme Design Stage. In a similar way to the software tool that was developed for the Outline Design Stage (ODS-Interface), the efficient application of simulation at the Scheme Design Stage would also best be achieved with the development of tools and functionalities tailored towards the requirements of the Scheme Design Stage. These programs could also utilise software components of the ODS-Interface, such as the DBMS program and the CAD link.

Specifications for a SDS-Interface and performance predictions analysis tool for this design stage were described in this thesis. One aspect was the increased relevance of lighting considerations in this design stage. This would make it beneficial to have closer links between thermal simulation and lighting simulation (although links would of course bring benefits at any design stage). Another aspect was the fact that simulation exercises typical for the Scheme Design Stage are currently mainly carried out by simulation experts. It would be desirable if architects could also carry out these exercises since the information gained from the performance predictions often affect aesthetic considerations (e.g. window dimensions).

When applying a SSDP at the Scheme Design Stage a simulation exercise would often be carried out with the aim of optimising a space or solving a performance problem identified. With potentially a considerable number of design parameters being appropriate to address such issues the number of Design Versions produced can be considerable. Data mining could possibly support the designer in this comparative analysis. An evaluation would need to be undertaken of its usefulness at the Scheme Design Stage. Of benefit could be the fact that data mining can carry out a combined assessment of both categorical and continuous data. Examples for categorical data definitions to use in an analysis are control schemes for blinds and ventilation strategies. The option of such a data definition would be useful when analysing a data set that contains performance predictions from different Design Versions.

8.4.4 Further CAD developments

Restrictions and limitations by CAD tools still impose problems on a designer who wants to use them to specify the geometry of a simulation model. Examples are:

- When using a CAD software to specify a simulation model designers can still not use the tool as pragmatic as they normally do but need to follow a number of conventions (Section 6.3.3 has outlined some of the issues and resulting QA requirements).
- It is not possible to re-import a model geometry definition into a CAD tool once it has been imported by a simulation tool and attribution of the model has commenced.

However, section 7.4.1 has also emphasised the importance designer give to the fact of being able to use a CAD tool for the specification of a model geometry. Therefore research and developments should be carried out to remove the above stated limitations of the tool.

8.4.5 Life cycle costing and embodied energy

It was indicated in the specification for the ODS-Interface that the software should be structured in a way that makes it possible to link the software tool to other design aspects. Life cycle costing was identified as particularly useful because it relates energy savings predicted from a simulation run to issues such as the additional initial investment cost, payback periods, etc. The integration of these functions into a simulation program is again supported by the fact that the ODS-Interface uses a DBMS and that simulation models are based on the concept of zones and surfaces – entities that are required to undertake costing exercises. Cost data is available in an electronic database format for construction cost [Spon 2002]; other databases also cover life cycle data of buildings [Spon 1999].

In addition to the life cycle cost the analysis could also address embodied energy of a building. Research currently underway in both the fields of life cycle costing and embodied energy will potentially be implemented into the ODS-Interface (the research is carried out by Hobbs [2002]).

8.4.6 Comparative analysis of Design Options/Versions

Predictions obtained from a simulation exercise will often be evaluated in a comparative analysis of different Design Options and/or Design Versions. Research into how to support such analysis is underway without yet having been implemented into simulation programs. Examples are global performance predictors that combine aspects such as cost, comfort and energy consumption, or a more differentiated assessment by applying methods such as fuzzy logic [Witlox et al 1997]. Examples for other approaches are described in Doggart [1995], Mahdavi et al [1998], de Hoog et al [1998], Bax et al [2000]. This would allow the high level comparative analysis of different building designs, which could then be supported by more in depth analysis functions such as these introduced in this thesis.

8.4.7 Uncertainty of input data

Uncertainty was identified in chapter 2 as another barrier for the application of simulation within the building design process. Such an analysis could be carried out in a manner as described by Macdonald [2002], who has implemented uncertainty analysis techniques into the fully functional ESP-r interface. Further research is however necessary to enable the routine application of uncertainly analysis as part of a simulation exercise.

8.5 Perspective

During the survey among designers who used simulation on design projects all but one participant stated that they are convinced that simulation will at some point be a routinely applied DDSS to address energy and environmental issues in the building design process (however, predictions of when it would occur varied significantly).

With the research described in this thesis a contribution has been made towards the accomplishment of such a design situation. However, additional developments as described above are needed to further support this process. It is envisaged that developments over time will result in simulation tools that have the characteristics of 4th generation tools as described in chapter 2, allowing a quick and easy model definition that will be generally applied in the building design process.

References

Bax T, Trum H, Nauta D, "Implications of the Philosophy of CH. S. Peirce for Interdisciplinary Design: Developments in Domain Theory", Proceedings of the 5th International Conference on Design and Decisions Support Systems in Architecture and Urban Design Planning, Eindhoven, pp 25-46, 2000.

De Hoog J, Hendriks N A, Rutten P G S, "Evaluating Office Building with MOLCA (Model for Office Life Cycle Assessments)", Proceedings of the 4th International Conference on Design and Decision Support Systems in Architecture, Eindhoven (CD format), 1998.

Doggart J, "How green is my office? The Office Toolkit", The Architect's Journal, August 1995, pp 44-45, 1995.

ESRU, "ESP-r: A Building and Plant Energy Simulation Environment: User Guide Version 10 Series", University of Strathclyde, Glasgow, 2002.

Hobbs D, Personal Communication, 2002.

Macdonald I A, "Quantifying the Effects of Uncertainty in Building Simulation", PhD Thesis University of Strathclyde 2002.

Mahdavi A, Ilal M E, Mathew P, Ries R, Suter G, "Aspects of S2", Proceedings of CAADfutures 99 Conference, Atlanta, GA, USA. pp 185 - 196, 1999.

Mahdavi, A, Akin O, Zhang, "Formalisation of Concurrent Performance Requirements in Building Problem Composition", Proceedings of the 4th International Conference on Design and Decision Support Systems in Architecture, Eindhoven (CD format), 1998.

Spon, "Spon's Architects' and Builders' Price Book 2003", Spon Press, 2002.

Spon, "The BPG Building Fabric Component Life Manual", Spon Press, 1999.

Witlox F, Arentze T, Timmermans H, "Constructing and consulting fuzzy decision tables", chapter 9 from "Design Support Systems in Urban Planning", E&FN Spon, pp. 157-173, 1997.

THE ODS-INTERFACE DATA MODEL

This Appendix explains the ODS-Interface Data Model. Figure A.1.1 displays the different entities of the data model and their relationships (boxes representing Support Databases are bordered by a double line). On the following pages a description of the different entities is given.

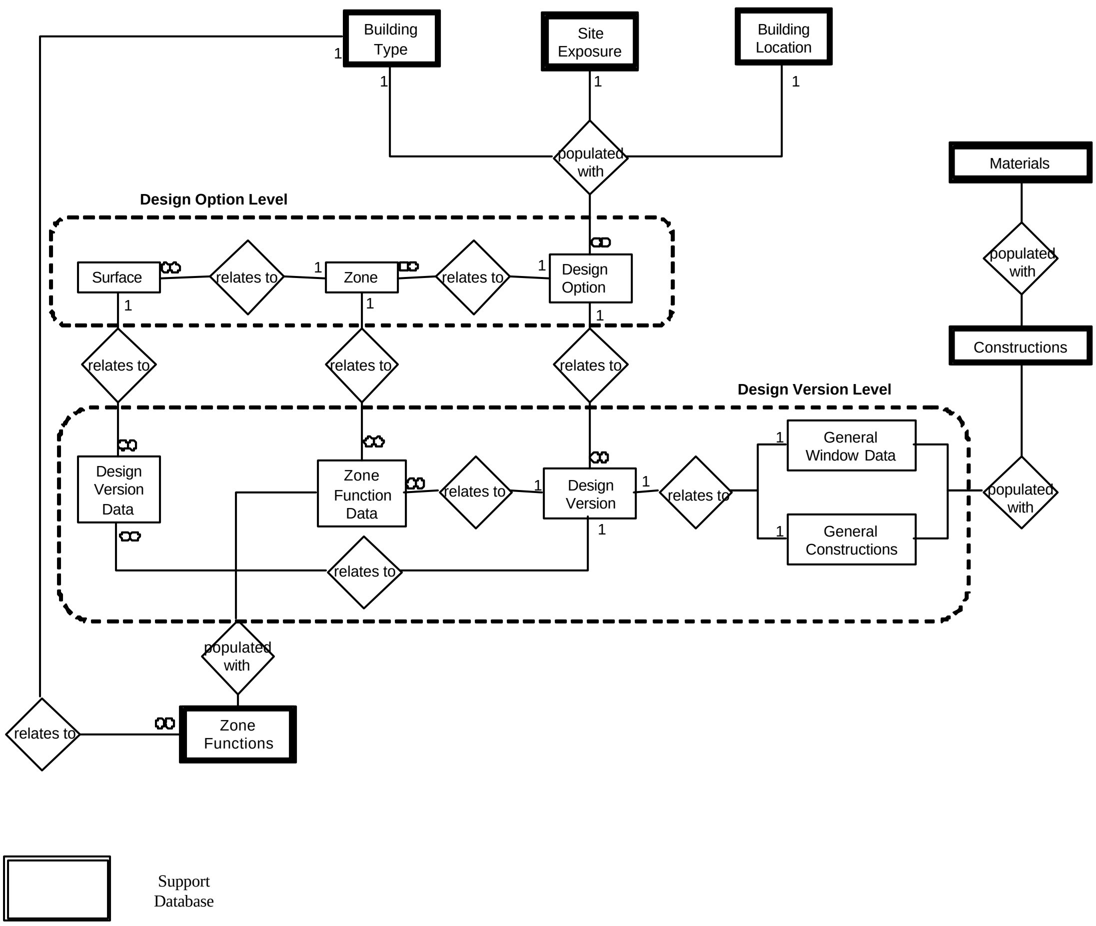


Figure A.1.1: The different entities of the data model and their relationships

Entity: Building type

The entity building type is required to control the provision of appropriate zone function Support Databases during the Design Version attribution process. It is also used to control the use of the correct ESP-r control file when the simulation model of a Design Version is created.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
Name	Text	Name of building type.
ControlFileName	Text	Name of ESP-r control file to be used with this Building Type.

Entity: Site exposure

The side exposure (a data specification required in every ESP-r model) is specified in ESP-r format but also with an extended text to be displayed by the ODS-Interface.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
ESPrName	Text	Name of side exposure as it appears in the ESP-r model.
FormName	Text	Name of side exposure as it appears in the ODS-Interface.

Entity: Building location

Associated with each building location are the longitude and latitude and the climate set which is to be used in a simulation run.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
Name	Text	Name of building location.
Longitude	Number	Longitude of building location.
Latitude	Number	Latitude of building location.

Entity: Design Option

Apart from documentation attributes the entity contains for each Design Option data about the project it is associated with, general information taken from Support Databases (building type, building location, site exposure) and factors for zone scaling.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
Name	Text	Name of Design Option.
ShortName	Text	Short name of Design Option (used by ESP-r).
Memo	Text	Memo of Design Option (more detailed information, e.g. for reports).
Project	Text	Project the Design Option is associated with.
BuildingTypeID	Number	Building Type (foreign key from entity “building type”).
BuildingLocationID	Number	Building Location (foreign key from entity “building location”).
SiteExposureID	Number	Site Exposure (foreign key from entity “site exposure”).
Scaling A	Number	Scaling for zone group A.
Scaling B	Number	Scaling for zone group B.

Entity: Zone
Apart from documentation attributes the entity contains for each zone instance data about the Design Option it is associated with, its surface number and its zone scaling factor.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
DesignOptionID	Number	Design Option the zone is associated with (foreign key from entity "Design Option").
Name	Text	Name of the zone.
Description	Text	Description of zone (more detailed information, e.g. for reports).
CountSurfaces	Number	Number of surfaces in a zone (required to create ESP-r connection file).
ZoneScaling	Number	Scaling factor the zone is related to.

Entity: Surface
Apart from its name each surface instance contains information about the zone it is related to, its tilt and environmental conditions on the other side and the number of vertices it comprises.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
ZoneID	Number	Zone the surface is related to (foreign key from "entity zone").
Name	Text	Name of the surface.
Tilt	Text	Tilt of surface (required for automatic attribution of surfaces with constructions).
Environment	Number	Environmental conditions on the other side of surface (required for automatic attribution of surfaces with constructions).
CountVertices	Number	Number of vertices in a surface.

Entity: Materials
Material definition includes a name, an associated material group and thermal properties.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
Material Group	Text	Group the material is associated with (e.g. concrete, brick etc.). This is used for a pre-selection when associating a material with a construction layer.
ESPName	Text	Name of construction (same as in ESP-r).
Conductivity	Number	Conductivity is required to calculate the U-value of a construction.
Density	Number	Density - kept for documentation.
SpecificHeat	Number	Specific heat - kept for documentation.
Emissivity	Number	Emissivity - kept for documentation.
SolarAbsorption	Number	Solar absorption - kept for documentation.
DiffuseResistance	Number	Diffuse resistance - kept for documentation.

Entity: Construction

Apart from documentation attributes the entity contains for each construction instance the overall construction layer number, data for each layer, optical properties and data to utilise the support database in the ODS-Interface and with the full ESP-r system (construction type, ESP-r code, ESP-r page).

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
FormName	Text	Name of construction as it appears in ESP-r.
ESPrName	Text	Name of construction as it appears in the ODS-Interface.
ConType	Text	Type of construction (façade, sloped roof, etc). Used to control the provision of appropriate constructions during attribution process.
ESPrCode	Text	Letter associated with construction in full ESP-r system (required to create scripts to attribute constructions to the thermal model using the full ESP-r system).
ESPrPage	Number	Page number associated with construction in full ESP-r system (required to create scripts to attribute constructions to the thermal model using the full ESP-r system).
Type	Text	Type – opaque or transparent.
OpticalProperty	Text	Name of optical property set of construction.
LayerNumber	Number	Number of layers in construction.
For each layer: Material	Number	For each layer: material type.
For each layer: Thickness	Number	For each layer: thickness.

Entity: Zone function type

For each zone function type documentation attributes are provided along with ESP-r specific data required to attribute it to the thermal model. The attributes 'building type' and 'zone function data' control the provision of appropriate data during the model attribution process.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
Name	Text	Name of zone function type.
OperationFile	Text	ESP-r operation file associated with zone function type.
ControlValue	Number	Control file value (function number) associated with zone function type.
BuildingType	Number	Building type associated with zone function type. Used to control the provision of appropriate instances during attribution process.
ZoneFunction	Text	Zone is used as a pre-select before the specification of the zone function type (e.g. treatment room).
ZoneFunctionType	Text	Zone function type (e.g. treatment room with night time cooling, high internal heat gains, etc).
Memo	Text	Description of zone function type.
OperationFileText	Text	Text of ESP-r operation file associated with zone function type.

Entity: Design Version

Apart from documentation attributes the entity contains for each Design Version information about the Design Option it is related to, its orientation and findings from the simulation exercise.

Attribute Name	Attribute Variable Type	Attribute Description
ID	AutoNumber	Unique identification number for every instance.
DesignOptionID	Number	Design Option the Design Version is related to (foreign key from entity "Design Option").
Name	Text	Name of Design Version.
ShortName	Text	Short name of Design Version (used by ESP-r).
Memo	Text	Memo of Design Version (more detailed information, e.g. for reports).
Orientation	Number	Orientation of building in Design Version.
ResultsMemo	Text	Memo of findings from simulation exercise.

Entity: General construction

The general construction specifies for each Design Version instance the constructions that are automatically attributed to the different surfaces (after that the user can locally specify a different construction).

Attribute Name	Attribute Variable Type	Attribute Description
DesignVersionID	Number	Design Version the general construction definition is related to.
FaçadeID	Number	General façade construction (foreign key from entity "construction").
SlopedRoofID	Number	General sloped roof construction (foreign key from entity "construction").
FlatRoofID	Number	General flat roof construction (foreign key from entity "construction").
PartitionsID	Number	General partition construction (foreign key from entity "construction").
FloorCeilingConstrID	Number	General floor ceiling (intermediate floor) construction (foreign key from entity "construction").
GroundFloorID	Number	General ground floor construction (foreign key from entity "construction").

Entity: General window data

The general window data specifies the constructions that are automatically attributed to each external vertical surface (after that the user can locally specify a different glass type or façade percentage but cannot change the frame properties).

Attribute Name	Attribute Variable Type	Attribute Description
DesignVersionID	Number	Design Version the general window data definition is related to.
Glazing TypeID	Number	Glazing type to be used for a window (foreign key from entity "construction").
PercentageOfFacade	Number	Area percentage of façade the window covers.
FrameYesNo	Boolean	Specification if window frame has been considered.
FrameTypeID	Number	Frame used for a window (foreign key from entity "construction").
FramePercOfWindow	Number	Area percentage of window the frame covers.

Entity: Design Version data

The Design Version data specifies for each surface the construction and window properties. In the first place the data is populated in logical processes with data from the entity 'general Construction' and 'general window data'. After that the user of the program can amend this definition.

Attribute Name	Attribute Variable Type	Attribute Description
DesignVersionID	Number	Design Version the Design Version data definition is related to.
SurfaceID	Number	Surface the Design Version data is related to (foreign key from entity "surface").
ConstructionID	Number	Construction used in Design Version data (foreign key from entity "construction").
PotentialWindow	Boolean	Specification if a window can potentially be included into surface (windows can for QA purposes only be included into vertical external surfaces).
WindowYesNo	Boolean	Specification if a window has been included into surface.
GlazingTypeID	Number	Glazing type to be used for a window (foreign key from entity "construction").
PercentageOfFacade	Number	Area percentage of façade the window covers.

Entity: Zone function data

The zone function data specifies for each zone the zone function type and if a comfort assessment is going to be carried out.

Attribute Name	Attribute Variable Type	Attribute Description
DesignVersionID	Number	Design Version the zone function data definition is related to (foreign key from entity "Design Version").
ZoneID	Number	Zone the zone function data definition is related to (foreign key from entity "zone").
ZoneFunctionTypeID	Number	Design Version the zone function data definition is related to (foreign key from entity "zone function type").
ComfortYesNo	Boolean	Specification if a comfort assessment ought to be carried out for this zone.

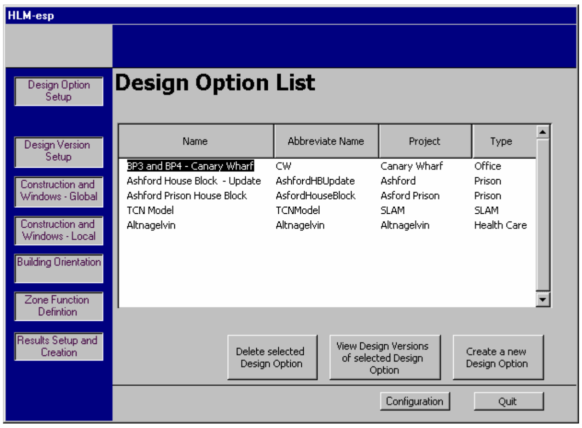
APPENDIX 2

SIMULATION MODEL CREATION WITH THE ODS-INTERFACE

This Appendix describes the process of creating Design Options and Design Versions with the ODS-Interface along with a description of other user functions the program provides.

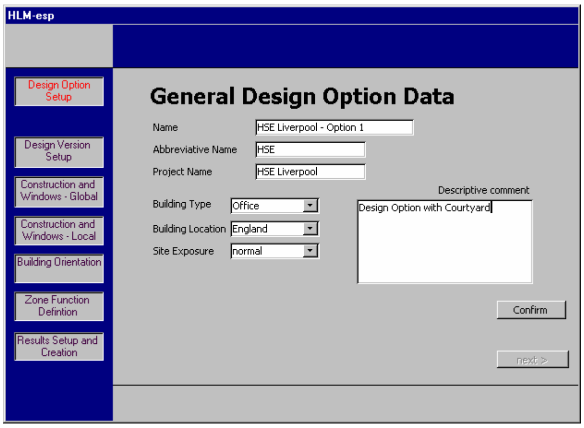
Main window/Design Option navigator

The window displayed below opens up when the user start the ODS-Interface. It displays a list of all past Design Options created. From here the user can delete an existing Design Option, create a new one or view the Design Versions of a Design Option. The process of creating a new Design Option and then Version is described in the following. It is carried out in sequence as described in the following, but it is also possible to carry out certain task independently (e.g. creation of a Design Option based on a Design Version that has been specified previously).



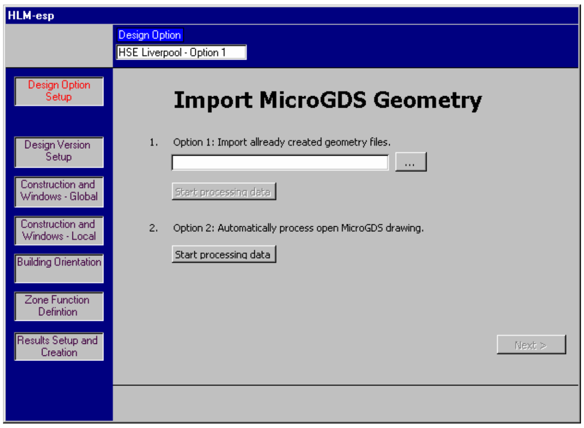
General Design Option data

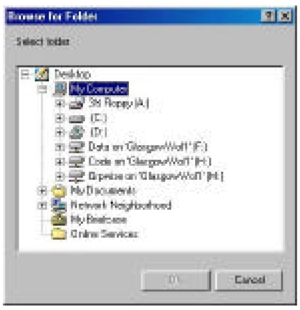
The creation of a new Design Option starts with the specification of its name, related project, building type (support databases available to the user during the attribution process depend on the building type of the Design Option), the building location (the climate set used depends on the location of the building) and the site exposure.



Geometry import

In a second step the user needs to import the geometry files that should be used for the simulation model. It is possible to import geometry files that have been pre-created (Option 1), in which case the user needs to point to the folder where the files are located. It is also possible to create files during the import procedure itself (Option 2). For the later choice the MicroGDS drawing needs to be open during the import.

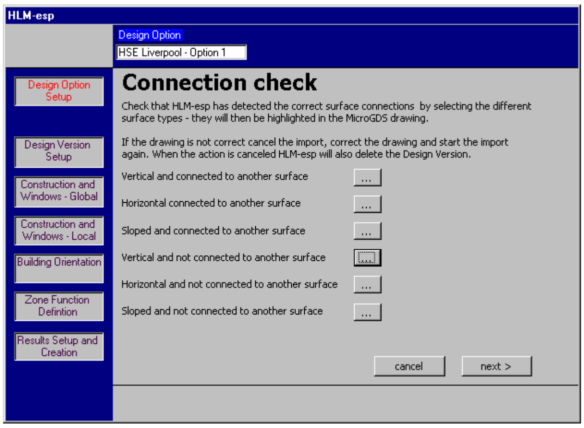


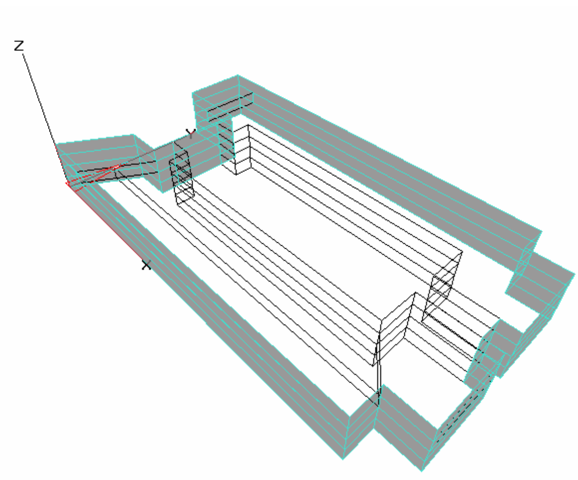


`

Connection check

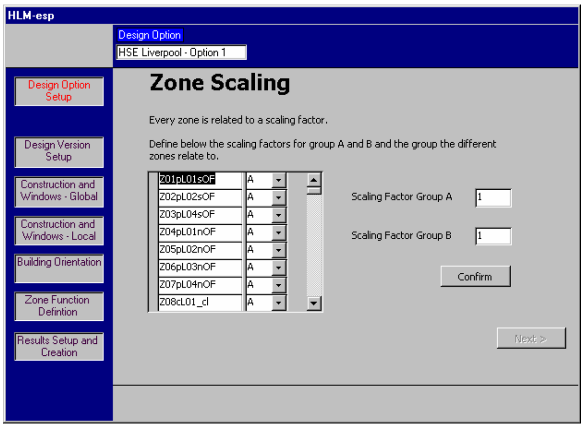
The CAD drawing passes information about zones and surfaces but does not provide data about surface inclination and connections. Since this data is required later during the automatic construction attribution process these properties are determined as part of the geometry import process. In this window the user can check if the data determined from the drawing is correct (hence an appropriate geometry had been specified). Selected surface types (here vertical and not connected to another surface) are indicated in the CAD drawing.

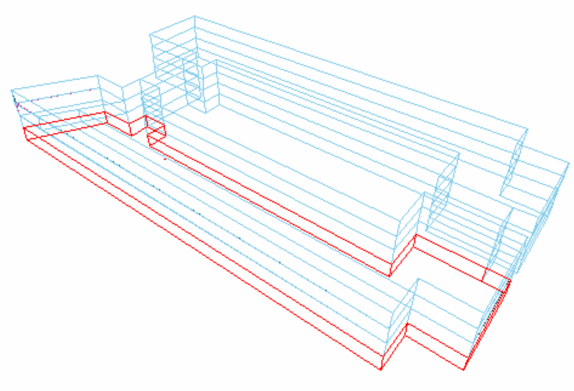




Zone scaling

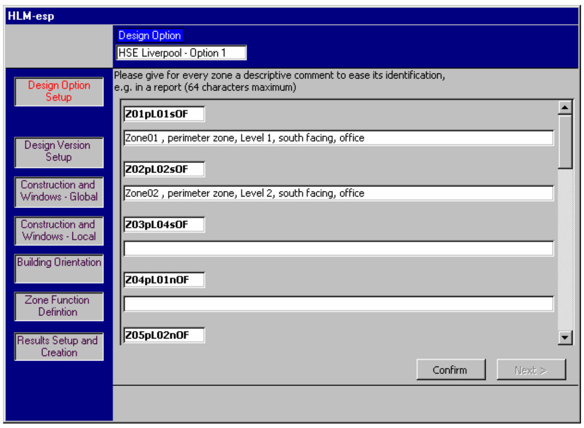
In case the user has specified repetitive sections of the building only once in the model it is possible to define zone scaling factors. Zones indicated to the user are during this process.





Zone description

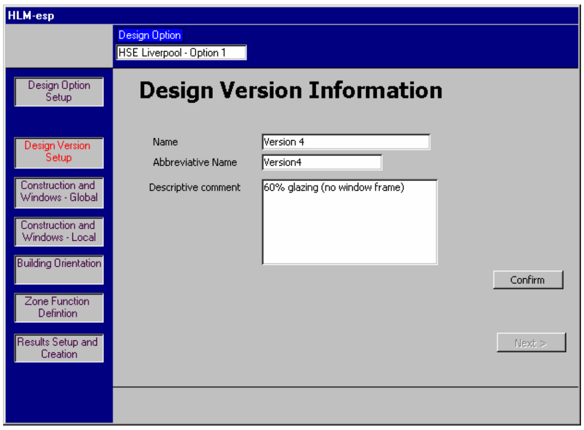
Zone description comments specified in this window can be used for reports or as a navigation aid for users who open the simulation model with the fully functional ESP-r interface. This is also the last step involved in the creation of a Design Option. Zones are indicated to the user during the data specification process.



`

Design Version Data

The creation of a new Design Version starts with the specification of its name and other documentation entities.

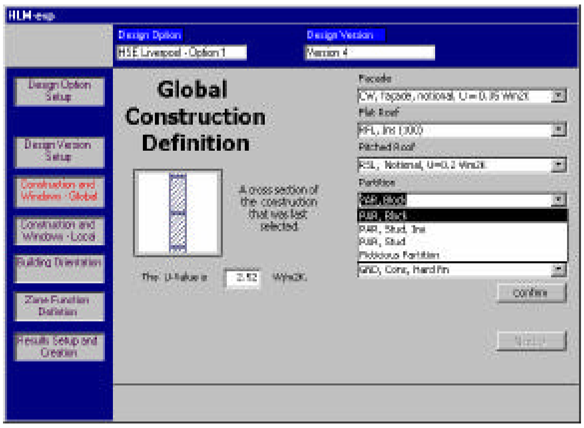


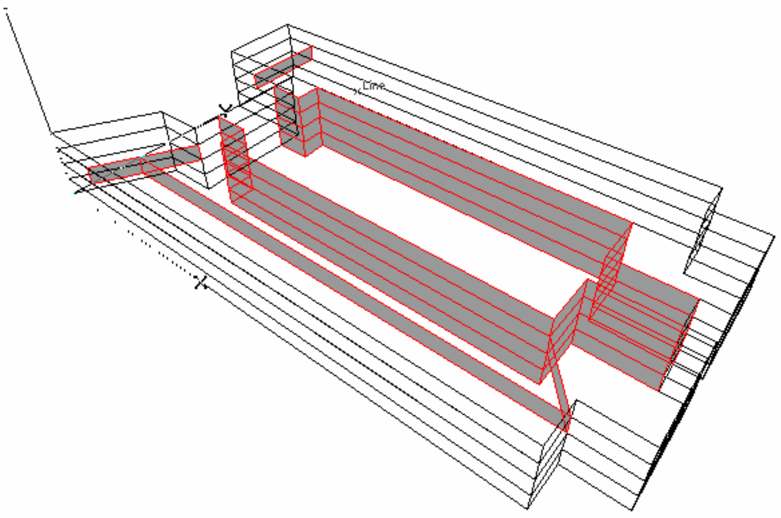
General constructions

General constructions that are specified in this window are globally attributed to all surfaces in the model. The attribution follows conventions as set down in the table below. Surfaces that relate to a specific selection are again indicated in the CAD drawing. When selecting a construction the user is also provided with an image of the construction and its U-value.

Construction	**Attributed to**
Façade	External and vertical surfaces.
Flat roof	External and upwards orientated surface.
Pitched roof	External and pitched surfaces.
Partition	Internal surfaces that are not upwards or downwards orientated.
Floor/ceiling gonstr.	Internal surfaces that are upwards or downwards orientated.
Ground floors	Internal surface that is downwards orientated and not internal.

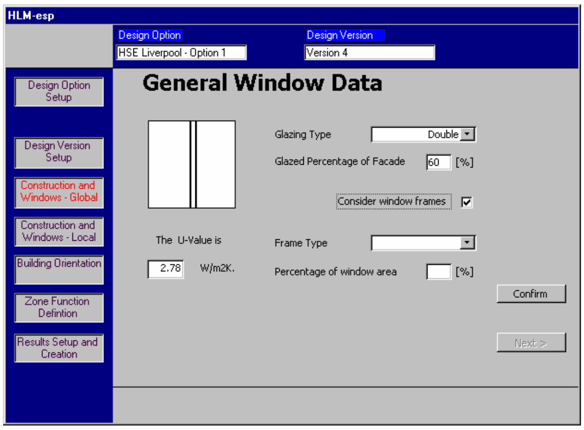
`

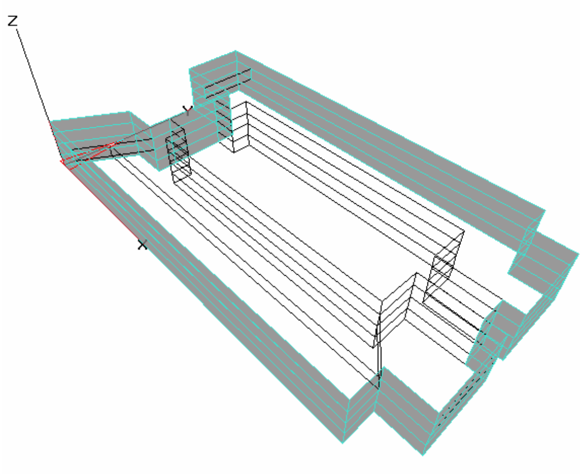




General window data specification

In a second global attribution stage the user specifies a general window size, glazing type and optional window frame properties. This data will be related to all external, vertical surfaces (these surfaces are again highlighted in the CAD drawing). Glazing within surfaces that have other properties (e.g. tilted roofs) needs to be specified as a local surface definition (see next window). When selecting a construction the user is again provided with an image of a cross section of the construction and its U-value.





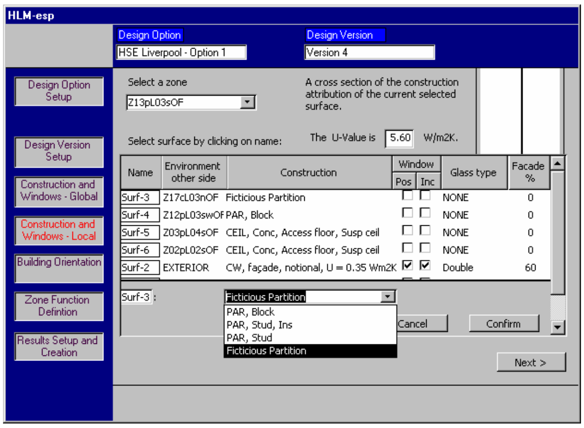
Construction and window definition local to a surface

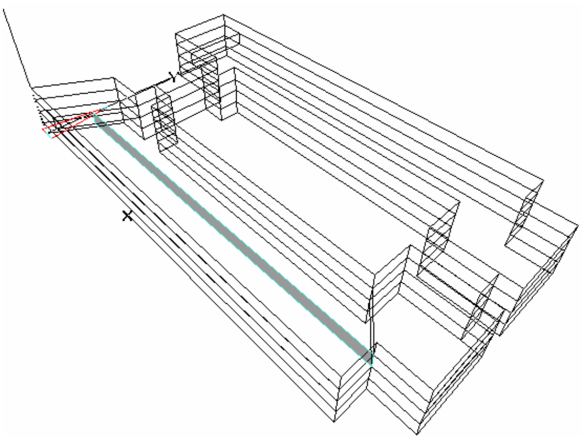
In this part of the model definition the user can make local changes to individual surfaces. These changes can be related to:

- The construction type of a surface.
- The environment on the other side of a surface.
- Exclusion or inclusion of windows into surfaces or changes of window areas and glazing type used.

The user specifies a surface by first selecting the zone it is related to and then the surface itself. Both entities are during this process indicated in the CAD drawing.

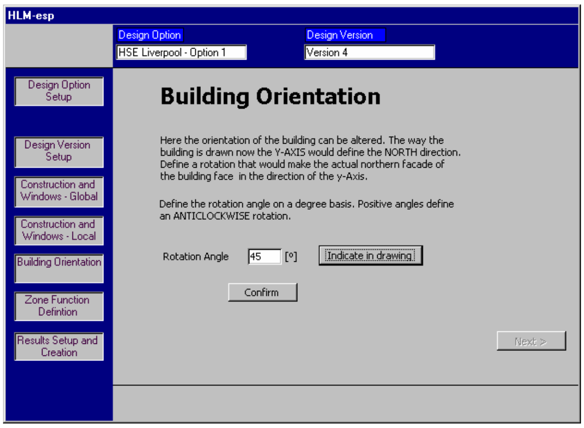
`



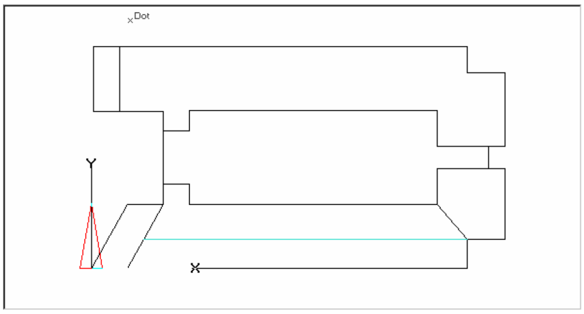


Building orientation

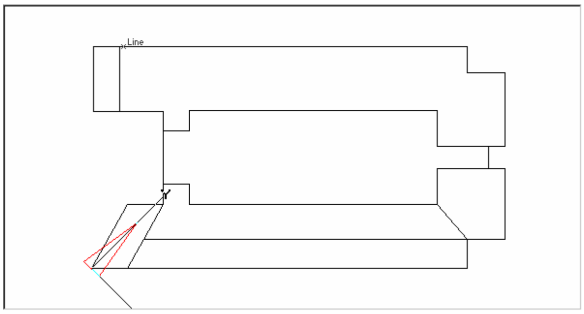
The MicroGDS drawing follows the convention that the y-axis defines the north direction. This is also indicated in the drawing with a red arrow pointing north. If this is not the appropriate orientation the building needs to be rotated. The user specifies this in the interface, which then also results in an alteration of the arrow in the CAD drawing.



`



Drawing as originally defined



Drawing after indicating a 45° rotation

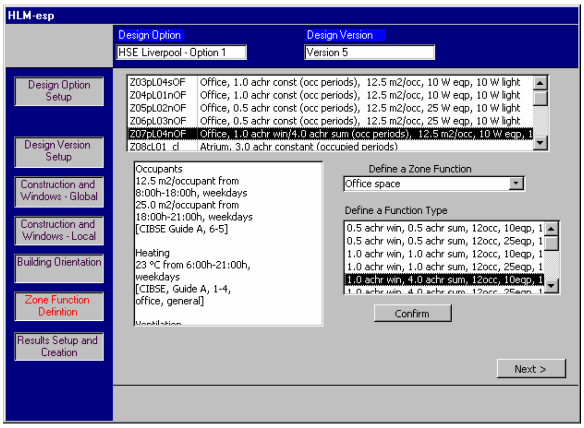
Zone function type

Heating and cooling control, ventilation rates and internal heat gains are defined in this window by specifying a zone function type. The attribution happens for each zone in a two-step process.

1. Zone function (e.g. office space).
2. Zone function type (e.g. 0.5 ac/h in winter and 4.0 ac/h in summer, 12 m^2/occupant, 10 W/ m^2 internal heat gains from lighting and 15 W/ m^2 from equipment).

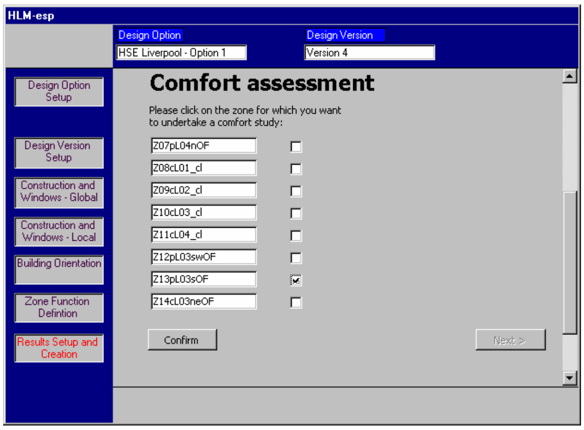
The zone that is currently subject to the attribution process is highlighted in the CAD drawing.

`



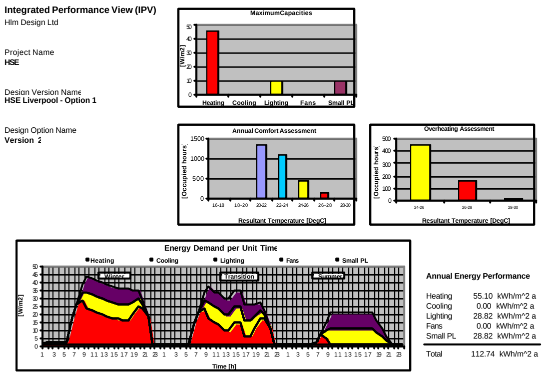
Comfort zone

As a last step in the model definition and as a precursor to producing an Integrated Performance View (IPV) the user needs to specify the zone(s) which will be the subject of comfort assessments.



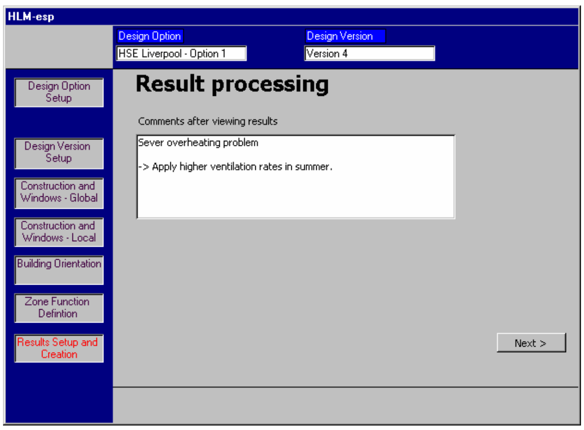
Performance predictions

After the user has specified all the relevant data the ODS-Interface automatically creates an attributed simulation model, performs a simulation and displays the performance prediction.



Results comments

After viewing the results of the simulation the user can take notes about the main findings from the analysis. This can then be included in the report of the particular Design Version, helping to put the simulation into the wider context of the study that was carried out.



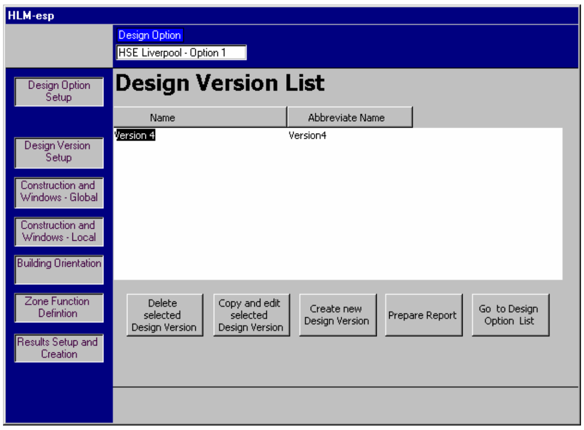
Design Version navigator

After the model creation, simulation and the display of the performance predictions the Design Version list opens up (this list can also be accessed from the Main Window that displays the Design Option list).

`

The window offers a number of user functions:

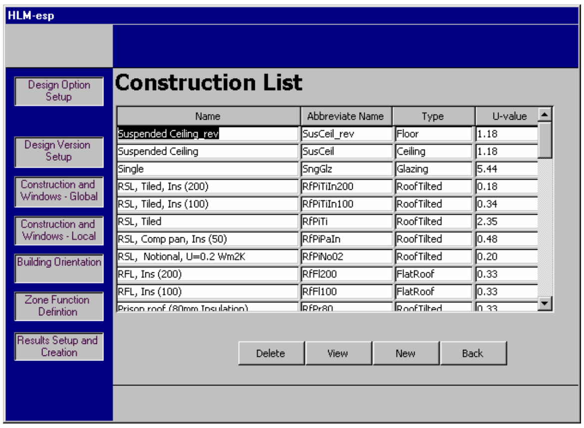
- delete a Design Version;
- copy and edit a Design Version;
- create a new Design Version;
- prepare report;
- go to Design Option list;



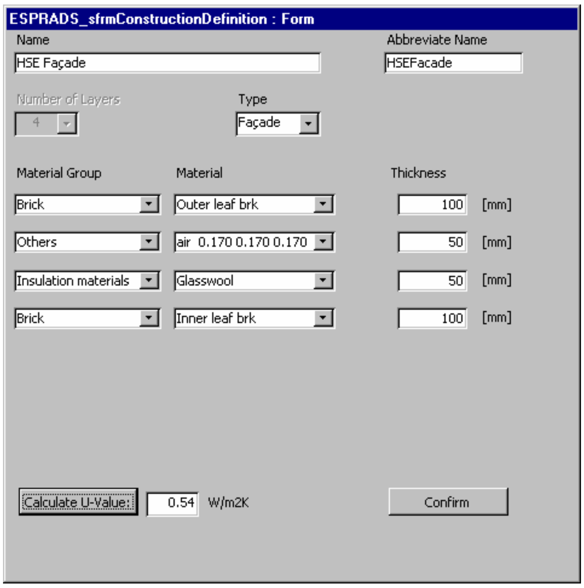
Other user functions

In addition to the creation of a simulation model the interface also supports other functions such as:

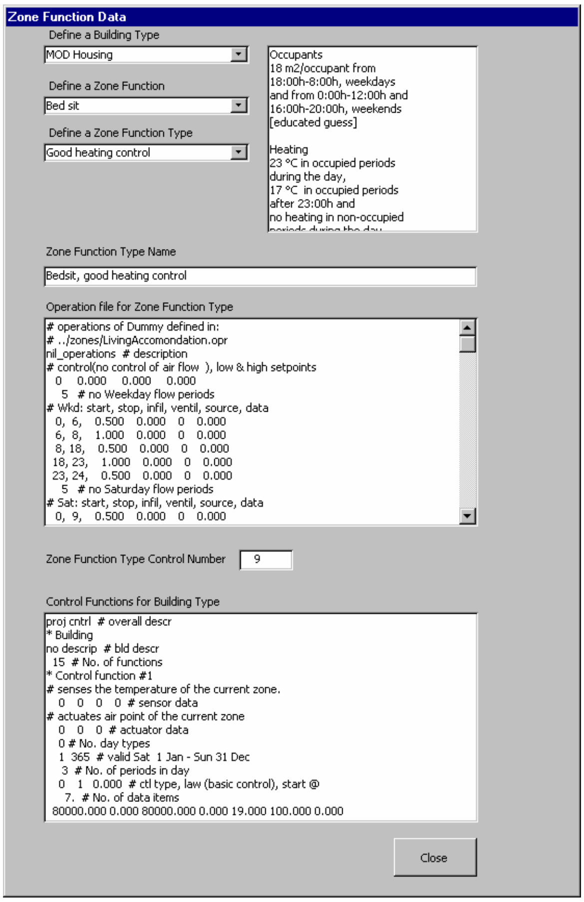
- the creation of a report that contains all important information of a Design Version;
- the viewing of the different constructions that are available from the support databases.



- the specification of new construction types;



- the viewing of zone function types available in the support databases.


Zone Function Data
Define a Building Type
MOD Housing
Define a Zone Function
Bed sit
Define a Zone Function Type
Good heating control
Occupants
18 m2/occupant from
18:00h-8:00h, weekdays
and from 0:00h-12:00h and
16:00h-20:00h, weekends
[educated guess]
Heating
23 °C in occupied periods
during the day,
17 °C in occupied periods
after 23:00h and
no heating in non-occupied
Zone Function Type Name
Bedsit, good heating control
Operation file for Zone Function Type
operations of Dummy defined in:
../zones/LivingAccomondation.opr
nil_operations # description
control(no control of air flow), low & high setpoints
0 0.000 0.000 0.000
5 # no Weekday flow periods
Wkd: start, stop, infil, ventil, source, data
0, 6, 0.500 0.000 0 0.000
6, 8, 1.000 0.000 0 0.000
8, 18, 0.500 0.000 0 0.000
18, 23, 1.000 0.000 0 0.000
23, 24, 0.500 0.000 0 0.000
5 # no Saturday flow periods
Sat: start, stop, infil, ventil, source, data
0, 9, 0.500 0.000 0 0.000
Zone Function Type Control Number
9
Control Functions for Building Type
proj cntrl # overall descr
* Building
no descrip # bld descr
15 # No. of functions
* Control function #1
# senses the temperature of the current zone.
0 0 0 0 # sensor data
actuates air point of the current zone
0 0 0 # actuator data
0 # No. day types
1 365 # valid Sat 1 Jan - Sun 31 Dec
3 # No. of periods in day
0 1 0.000 # ctl type, law (basic control), start @
7. # No. of data items
80000.000 0.000 80000.000 0.000 19.000 100.000 0.000
Close

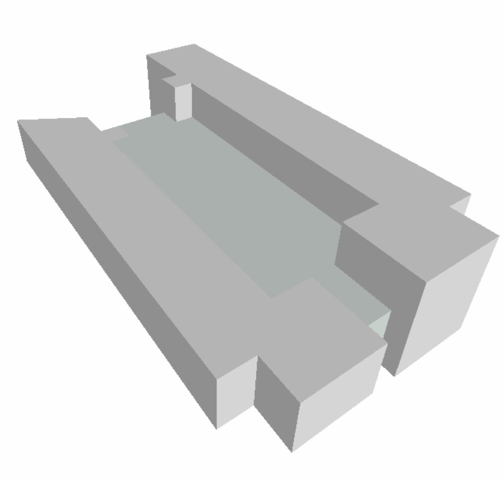
APPENDIX 3

SIMULATION REPORT CREATED BY ODS-INTERFACE

Ths Appendix contains examples of reports which can be created with the ODS-Interface (in the report named HLM-esp) and the full ESP-r system.

HLM-esp
Simulation Model Report

HSE Liverpool



HSE - Option 1

Model with courtyard

Version 1

Model attributed with parameters where a poor building performance could be expected

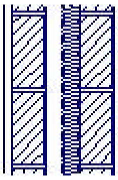
HLM Design
Riverside House
26(

23 October 2002

General Construction Definition

Facade Construction

CW, façade, notional, U = 0.35 Wm2K

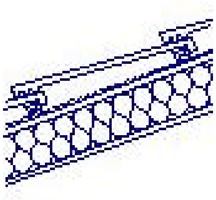


Partition

Glass panel

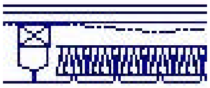
Sloped roof

RSL, Tiled, Ins (200)



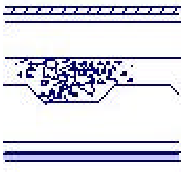
Flat roof

CW, roof, notional, U = 0.25 Wm2K



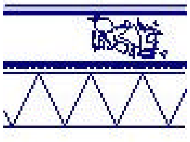
Intermediate floor construction

CEIL, Conc, Access floor, Susp ceil



Ground floor

GND, Conc, Soft fin



General Window Data Definition

Glazing Type:

Double

Window percentage:

90 % of the facade area are window openings

Frame Type:

Window frames included

☐

(No inclusion means windows are 100% glazed)

Window percentage:

0 % of the window composed of framing.

U-Values

Below are the U-Values for the default constructions and the default glazing type:

Note that only constructions are listed for surface types that formed part of the model.

Facade:	**0.35**	W/m2K.
Sloped Roof:	**0.18**	W/m2K.
Flat Roof:	**0.25**	W/m2K.
Glazing:	**2.78**	W/m2K.

Surface Attribution

Z01pL01s	**Surf-1**	Environment:	**EXTERIOR**	Surface tilt:	**VERT**	
Construction	**CW, façade, notional, U = 0.35 Wm2K**			Window:	**Double**	**90** %.
Z01pL01s	**Surf-2**	Environment:	**EXTERIOR**	Surface tilt:	**VERT**	
Construction	**CW, façade, notional, U = 0.35 Wm2K**			Window:	**Double**	**90** %.
Z01pL01s	**Surf-3**	Environment:	**EXTERIOR**	Surface tilt:	**VERT**	
Construction	**CW, façade, notional, U = 0.35 Wm2K**			Window:	**Double**	**90** %.
Z01pL01s	**Surf-4**	Environment:	**EXTERIOR**	Surface tilt:	**VERT**	
Construction	**CW, façade, notional, U = 0.35 Wm2K**			Window:	**Double**	**90** %.
Z01pL01s	**Surf-5**	Environment:	**EXTERIOR**	Surface tilt:	**VERT**	
Construction	**CW, façade, notional, U = 0.35 Wm2K**			Window:	**Double**	**90** %.
Z01pL01s	**Surf-6**	Environment:	**Z08cL01_c**	Surface tilt:	**VERT**	
Construction	**Glass pannel**			Window:	**NONE**	**0** %.
Z01pL01s	**Surf-7**	Environment:	**Z08cL01_c**	Surface tilt:	**VERT**	
Construction	**Glass pannel**			Window:	**NONE**	**0** %.

This report example only contains data for a few surfaces. With the same pattern are in a complete report surfaces of all zones documented.

Zone function attribution

Atrium, 0.75 achr constant (occupied periods)

Zones with this attribution | **Description of zone function**

Z08cL01_cl

Occupants
20 m2/occupant
9:00h-19:00h weekdays
and saturdays
11:00h-19:00h weekdays
and saturdays
[educated guess]

Ventilation
0.75 air changes/hour
in occupied periods
[educated guess]

This report example only contains data for one zone. With the same pattern are in a complete report all zones documented.

Building Orientation

In HLM-esp it is possible to change the orientation of the building.

With the way the building is originally drawn in MicroGDS the
Y-AXIS defines the NORTH direction.

The rotation angle is defined on a degree basis.
Positive angles define an ANTICLOCKWISE rotation.

The building was rotated for this design version by **0** º.

Results Comment

Energy consumption was well below good practice benchmark figures for heating (91 kWh/m^{2}a).

The resultant temperatures will lead to poor comfort conditions during long periods in both the atrium and the office space.

APPENDIX 4

SIMULATION MANAGEMENT PROCEDURES

Ths Appendix contains example pages of the simulation management procedures as specified during the resesearch.

Simulation Exercise Request

A1.1 Simulation Project Record

To be filled in by design project leader and simulation manager

Design project No ______________________________

Design project name ______________________________

Client name ______________________________
If applicable, for example in case of external request

Contact list (name, address, telephone number, email)
E.g. building owner, architect, services director

Name	Address	Tel No	e-mail	Company

Expand table using tab if required

A1.2 Purpose of simulation

The following lists simulation exercises that can be carried out with HLM-esp and design parameters that could be included into an evaluation. For questions regarding the use of HLM-esp for other purposes please contact the HLM Design simulation manager.

Tick required simulation

The minimizing of heating energy consumption

- Construction definition (insulation, massing)
- Fenestration definition (type and size) ☐
- Room type (internal heat gains, air change rates and heating control)

The minimizing of cooling energy performance

- Construction definition (massing)
- Fenestration definition (type and size) ☐
- Orientation
- Room type (internal heat gains, air change rates and cooling control)

Tick required simulation

Predicting internal (normally summertime) temperatures statistics ☐

- Construction definition (massing)
- Fenestration definition (type and size)
- Orientation
- Room type (internal heat gains and air change rates)

Optimization to reduce internal summer temperatures ☐

- Construction definition (massing)
- Fenestration definition (type and size)
- Orientation of building
- Room type (internal heat gains and air change rates)

The evaluation of natural ventilation strategies ☐

- Room type (air change rates)

Predicting heating plant capacity ☐

- Construction definition (insulation, massing)
- Fenestration definition (type and size)
- Room type (internal heat gains, air change rates and heating control)

Predicting cooling plant capacity ☐

- Construction definition (massing)
- Fenestration definition (type and size)
- Room type (internal heat gains, air change rates and cooling control)

The evaluation of different plant control configurations ☐

- Room type (control)

If uncertain about which exercise to carry out and/or how to specify the design parameters please contact either the HLM Design simulation manager or building services director.

A1.2 (continued)

Please specify purpose of simulation exercise

To be filled in by design project leader

This should include a brief description of the project in terms of the building(s) and key building functions (attach drawings or specifications if appropriate). Also provide your own interpretations of the key questions that you attempt to answer using simulation and if applicable specify which Design Options/Design Versions you would intend to create.

A1.3 Memo to HLM Design simulation manager

To be filled in and signed by design project leader

Send Appendix 1 – Simulation Exercise Request to inform HLM Design simulation manager about the potential simulation project

Memo sent by ________________________

A1.4 Specification of simulation Design Options and/or Design Version

To be filled in by design project leader, building services director or simulation manager

Design Option ☐ Design Version ☐ Tick appropriate selection

Example for Design Option: Assess impact of atrium on building performance
Example for Design Version: Evaluate benefit of high summer ventilation rates on summer comfort

Description

Explain in a description

Copy this page in case several Design Options and/or Design Versions need to be specified

A1.5 Specification of input time requirements

To be filled in by design project leader, building services director or simulation manager

Simulation manager	________	Hours ☐	days ☐
Design project leader	________	Hours ☐	days ☐
In-house simulation Quality control leader	________	Hours ☐	days ☐
General simulation Quality control leader	________	Hours ☐	days ☐
CAD manager	________	Hours ☐	days ☐
Building Services Director	________	Hours ☐	days ☐
University	________	Hours ☐	days ☐

A1.6 Specification of costs

To be filled in by design project leader or simulation manager

Design project construction value £ ________

Simulation project fee £ ________

A1.7 Specification of deadlines

To be filled in by design simulation manager

Date by when simulation strategy agreed ________

Date by when simulation model(s) created ________

Date by when report produced ________

A1.8 General approval

Simulation exercises (outlined in 1.2) ______________________

To be signed by design project leader,
building services director or simulation manager

Simulation cost (outlined in 1.4) ______________________

To be signed by design project leader

Date for report (outlined in 1.5) ______________________

To be signed by simulation manager

A1.9 Approval of external request

Sign in case a simulation exercise is requested from an outside party

Simulation exercises (outlined in 1.2) ______________________

To be signed by a director

A1.10 People involved

To be filled in by simulation manager

Architectural team responsible for co-coordinating the HLM-esp exercise

Simulation manager ______________________

Design project leader ______________________

Simulator ______________________

Quality control

In-house simulation quality control ______________________

General simulation quality control ______________________

APPENDIX 5

QUESTIONNAIRES

This Appendix contains the questionnaires that were used to obtain feedback from users of the ODS-Interface and designers who used performance predictions obtained from a simulation exercise on design projects.

QUESTIONNAIRE FOR USERS OF THE ODS-INTERFACE

1) What are your activities in the company (CAD, design, both, etc)

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____

____

2) How difficult did the user find it to carry out a simulation exercise?

Very difficult	Difficult	Slightly difficult	Not difficult

3) How difficult do you find the operation of ODS-Interface?

Very difficult	Difficult	Slightly difficult	Not difficult

4) How difficult did you find the definition of the model geometry with MicroGDS?

Very difficult	Difficult	Slightly difficult	Not difficult

5) Please give reasons for your choice above

____

____

____

6) Most simulation programs use their own CAD program to define a model geometry. How important was for you the option to use MicroGDS for this task?

Very important	Important	Not really important	Not important at all

7) Please indicate how important/not important you find different aspects related to the use of MicroGDS in conjunction with ODS-Interface (rather than using an additional CAD package with which you would have to define the geometry):

Very important - not important

Familiarity with MicroGDS functions.				
Fast data definition because existing drawing is used as a template for the definition of the model geometry.				
Improved QA because existing drawing is used as a template for the definition of the model geometry.				

8) What are the main differences between how you normally use MicroGDS and the way you have to apply it to create a model geometry (2D and 3D)?

____

____

____

9) How important do you find the guided input procedure for the ease-of-use of the program?

Very important	Important	Fairly important	Not important

10) How important is (for the ease-of-use of the program) the fact that the software has an in-built structure of Design Options and Design Versions and also deals with data maintenance and processing procedure?

Very important	Important	Fairly important	Not important

11) How important is the concept of support databases (rather than having to redefine the data with every project) for the ease-of-use of the program?

Very important	Important	Fairly important	Not important

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12) What are the main difficulties when using simulation?

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____

13) Would you also like to be able to define data in the support databases yourself or do you prefer to leave this to the system administrator?

Strong preference for data definition	Preference for data definition	Less preference for data definition	No preference for data definition

14) Please give reasons for your choice above

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____

15) What do you see as important QA implications when using simulation?

____

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____

16) How relevant is QA in simulation in comparison with other design work you normally carry out?

Much more relevant	More relevant	Equally relevant	Less relevant	Far less relevant	Not comparable

17) How would you compare a simulation exercise to work you normally carry out?

____

____

____

18) Do you have any other general comments related to the use of simulation in the design process?

____

____

____

QUESTIONNAIRE TO DESIGN TEAM

1) For how long have you worked as an architect?

_______ years

2) For how long have you worked with HLM?

_______ years

3) What are your activities in the company (management, design, etc)

____

____

____

4) Did you know about building simulation before HLM started using it?

Yes	No

5) Did you apply building simulation before HLM started using it?

Yes	No

6) If yes answer to previous question is yes, how did you apply it?

____

____

____

7) Do you know any other energy and environmental design support tools?

____

____

____

8) How did you so far address energy and environmental issues in design?

____

____

____

9) Why do you think Architects do generally not use simulation programs themselves?

____

____

____

10) Did you find the performance prediction presentation was appropriate?

Very much	Much	Not really	Not at all	No opinion

Comments

____

____

____

11) How relevant is QA when applying simulation?

Very relevant	Relevant	Not really relevant	Not at all relevant

Comments

____

____

____

12) How relevant is liability when applying simulation?

Very relevant	Relevant	Not really relevant	Not at all relevant

Comments

____

____

____

13) Do you think simulation can bridge the gap towards other practitioners (e.g. M&E)?

Very much	Much	Not really	Not at all	No opinion

Comments

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____

____

14) What do you think can catalyse the use of simulation within the building design process?

____

____

____

15) Do you think that PFI/PPP projects have been an important vehicle for the integration of building simulation into the design process?

Very much	Much	Not really	Not at all	No opinion

Comments

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____

16) What advantages do you see in the in-house application of simulation rather than by external consultants?

____
____
____

17) Are you convinced that simulation will find a place in the construction industry as a design support tool?

Very convinced	Convinced	Not really convinced	Not at all convinced	No opinion

Comments

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____
____

18) If you think simulation will find a place in the construction industry, what do you think how long this will take?

_____ years.

19) Can you identify any potential problems regarding the use of simulation in the design process?

____
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