INTEGRATED APPROACH TO ARCHITECTURAL DESIGN PROCESS THROUGH INFORMATION TECHNOLOGY

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of
MASTER OF ARCHITECTURE

By

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'Buildings, too, are children of Earth and Sun'

Frank Lloyd Wright (1867-1959)

CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the dissertation, entitled **"INTEGRATED APPROACH TO ARCHITECTURAL DESIGN PROCESS THROUGH INFORMATION TECHNOLOGY"** in partial fulfillment of the requirement for the award of the Degree of **MASTER OF ARCHITECTURE** submitted in the **Department of Architecture & Planning** of the Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during the period from July 2005 to June 2006 under the supervision of **Prof. S. Y. Kulkarni.**

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Place: Roorkee

(SUDHEER BABU T. V.)

Dated: June 22nd, 2006

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Preservation of energy resources, occupant comfort and environmental impact limitation are the key issues of modern and sustainable architecture. A multiple-view assessment of building performance at the design stage is therefore essential in order to prevent the delivery of buildings that do not comply with modern constraints. For more than a quarter of a century, building simulation programs have been developed to support non-trivial performance appraisals. In general, these programs deal with a small sub-set of the overall problem. To obtain a global view, solutions that permit stand-alone programs to inter-operate by sharing and exchanging common sets of information have therefore been developed. However, these solutions do not support dynamic information exchange and their complicated data management may lead to result inconsistency. Even if computer technology has rapidly evolved during the last few decades, a satisfactory level of integrated building representation has not been achieved so far, neither horizontally between different views nor vertically between all the processes that occur during the project life span.

This thesis presents the developments, implementation and application of an extensive building representation which supports the integrated assessment of building performance. This new development supports various views performance throughout the building life cycle in relation to performance domains such as energy consumption, lighting availability, occupant comfort (thermal, visual), room acoustics and the environmental impacts related to the construction materials and fuel streams over the whole building life span.

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 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).

The case study is 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 study shows how the application of simulation can result in a more informed decision making process and an improved design quality.

A key barrier to the acceptance of simulation within building design has been identified as the fact that it is not fully integrated into the design process. The thesis attempts to address this barrier by embedding modeling as a standard component of design practice procedures within an architectural practice.

Chapter 1 enlists the aims, objectives and limitations of this thesis outlining a methodology in which the study was conducted.

Chapter 2 points out the importance of using multiple-views during building design. It also gives the description of some constructive solutions developed in the past, which concurrently fulfill several assignments. It also illustrates the consequences of a lack of multiple-view assessment in appraising the building performance in modern architecture.

Chapter 3 reports different potential approaches to a multiple-view assessment of building performance. Although experimental methods are useful in various situations, the requirements of an integrated approach are better met by mathematical methods, especially computer simulation. This chapter scrutinizes the approaches developed in computer simulation to provide a multiple view assessment. Finally, this chapter analyses the capabilities of available integrated simulation programs, which leads to the conclusion that none of the available simulation applications can concurrently perform the assessment of the building performance (thermal, lighting, ventilation, acoustics), the occupant comfort and the environmental impacts over the whole life cycle of the building.

Chapter 4 presents a building case study to demonstrate the applicability of the integrated approach. It presents the overall performance obtained for an office building as predicted by ESP-r. The simulation results are compared with measurements monitored in the building during the post occupancy phase. This chapter does not have the pretension to validate the simulation, but rather to analyse the conformity of the simulation results with in-situ measurements.

Chapter 5 gives an overview of different types of building simulation programs that are available to building designers. Four such programs have been identified and have been compared.

Chapter 6 describes the 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. A concept, Simulation Support Design Process (SSDP) was developed identifying the key parameters which the designer might wish to evaluate in the identified stages of the design.

Chapter 7 concludes the thesis with a review of research contributions and suggestions for future research work.

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CHAPTER 1

INTRODUCTION

Historically, the use of simulation on practical problems is undertaken, predominantly, by specialized environmental systems engineers or research groups (commercial, government funded or academic), usually focused on specific problems. This situation gives rise to simulation exercises being undertaken, generally, later on within the design process (scheme or detail design stages) with the purpose of validating design decisions. This situation is due to the limited availability of resources for simulation work at early design stages and limited understanding of the benefits of using simulation by design team members. However, changes in procurement methods and legislation have provided strong incentives for the use of simulation within architectural practice.

The use of simulation facilitates better understanding of the design problem with respect to energy performance, often highlighting poor performance of design concepts: the need to change designs to mitigate this under-performance at the later design stages can be costly.

1.1 IDENTIFICATION OF THE PROBLEM

For more than a decade building simulation programs have been developed to support significant building performance appraisals. In general each of these programs deal with a small subset of the overall problem. There a variety of such programs which cater to various aspects of the building design. A good knowledge of the integration of these tools in professional design practice is absent.

Conventional design practices do not allow for the efficient use of these design tools owing to the nature of the information flow within the different stages of the project. The use of these simulation design tools needs a new outlook into the design practice and appraisal. To obtain a global view, solutions that permit standalone programs to inter-operate by sharing and exchanging common sets of information have therefore to be developed.

1.2 HYPOTHESIS

With the contemporary computer technology and tools, a satisfactory level of integrated building representation can be achieved between all the processes that occur during the project life span.

1.3 AIMS & OBJECTIVES

1.3.1 Aim

The aim of this study is to propose a methodology for the structured application of simulation in the building design process, an information flow model which facilitates the effective use of contemporary design tools.

1.3.2 Objectives

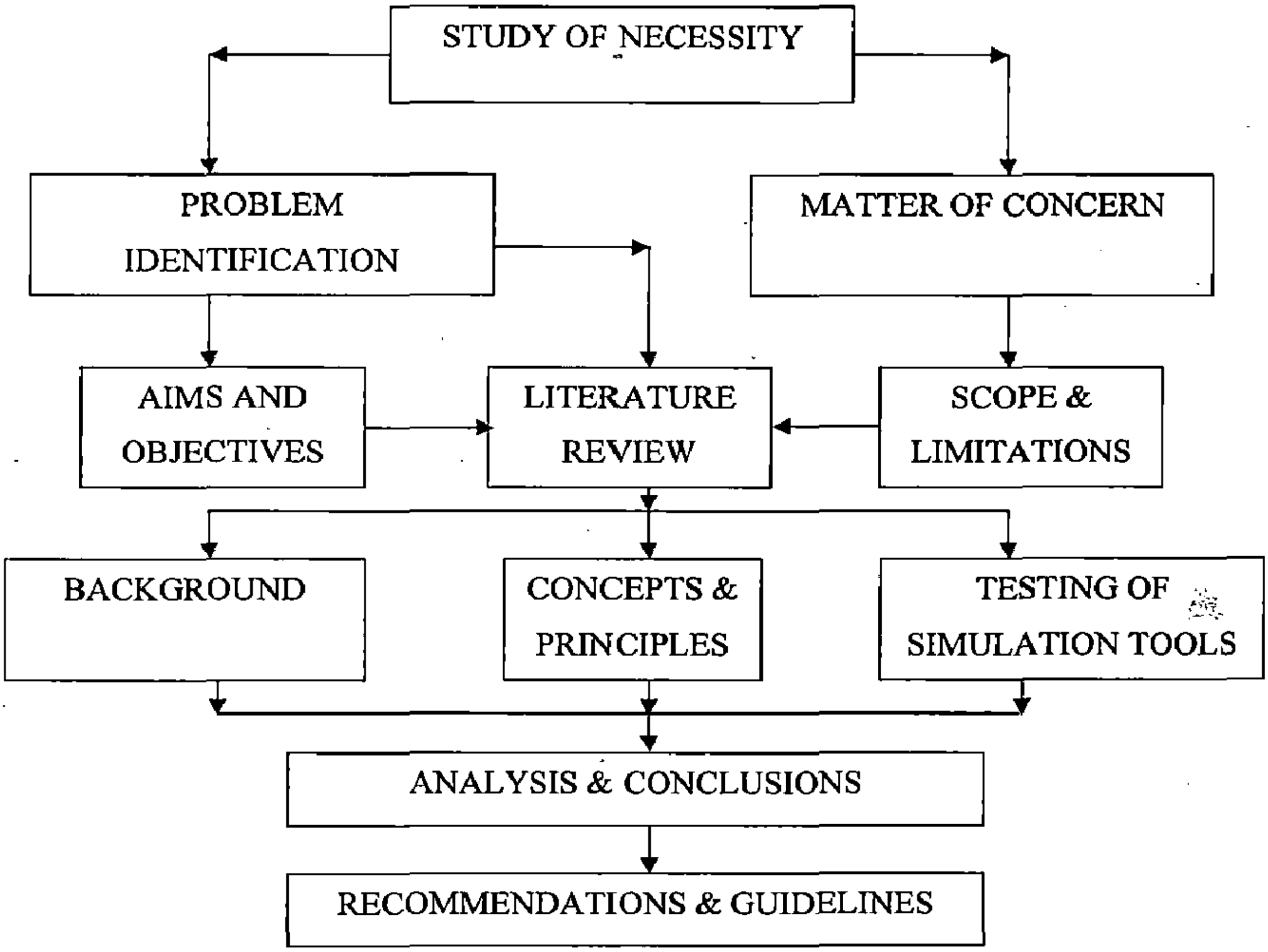
- To understand the basics of simulation and computer study models for simulation, the representation of results, etc. On a conceptual level, the study would comprise the analysis of existing tools, identification of relevant tools and their feasibility.
- To identify the various stages in the architectural design process and identify the stages in which simulation can be used to take informed decisions in the development of the project.
- To identify the various design parameters which can be tested through the existing tools in the design stages short listed.

1.4 SCOPE & LIMITATIONS

Aspects such as cost estimation, construction planning and related subjective aspects would not be considered in the study.

1.5 METHODOLOGY

The identification of the problem in this thesis called for a methodology which is quite different from the conventional methodologies. In addition to literature case studies, this research involves learning and working on available computer simulation tools and studying their appropriateness in the context of short listed stages of the architectural design process. The general work flow has been depicted in the flow chart below.



CHAPTER 2

INTEGRATED BUILDING PERFORMANCE FROM ANCIENT TIMES TO THE PRESENT

Every major civilization has developed architecture with characteristic lines as specific as its language, costumes or folklore. For thousands of years, the human has developed architectural concepts to provide acceptable comfort in a specific environment, taking into account local climatic conditions, available construction materials, as well as cultural and religious aspects. With modern architecture, an important concern of the scientific community is to resolve specific problems the building industry is confronted with. But the necessity for an efficient construction industry has brought forward new architectural concepts, whose performance assessment required also an integrated approach. This chapter presents several ingenious systems developed through time that could fulfill several assignments simultaneously and illustrates the consequences resulting of a lack of multiple-view assessment in appraising the building performance in modern architecture.

2.1 INTEGRATED ARCHITECTURE IN THE ANCIENT TIME

Vernacular architecture, which can be regarded as a sustainable and natural contract between man and nature, is the fruit of imagination, years of evolution and climatic requirements. It was limited to the local materials and techniques available at a given time. Transport was limited, which reduced the use of imported raw materials. This led to constructive concepts that took into account not only occupant comfort but also the local resources and the environmental impacts of the use of the construction. Vernacular architecture was able to provide many concepts to maintain comfortable conditions while striking a balance with the environment as it can be illustrated with the following examples.

Providing daylight and ventilation simultaneously was an important issue, which was solved in different ways. In the Ancient Egyptian Empire (2635-2155 BC), it was not conceivable to bore through the thick temple roof and walls. To solve the problem, small slots were pierced at the junction of the flat roof and the temple wall (Sphinx temple). Because of their size and location, these slots faintly lighted the upper part of the walls. In small temples or in dwellings, where the roof was thinner, small apertures were bored trough the roof-terrace, to improve day lighting and ventilation. The New Empire (1550-1080 BC) found a way to improve the efficiency of these apertures by taking advantage of the level difference between roof-terraces. For instance, in the Ammon temple in Karnak, louvers were pierced into vertical slabs (walls) to provide better ventilation and allow the light to enter obliquely, which avoided glare problems as shown in Figure 2.1.

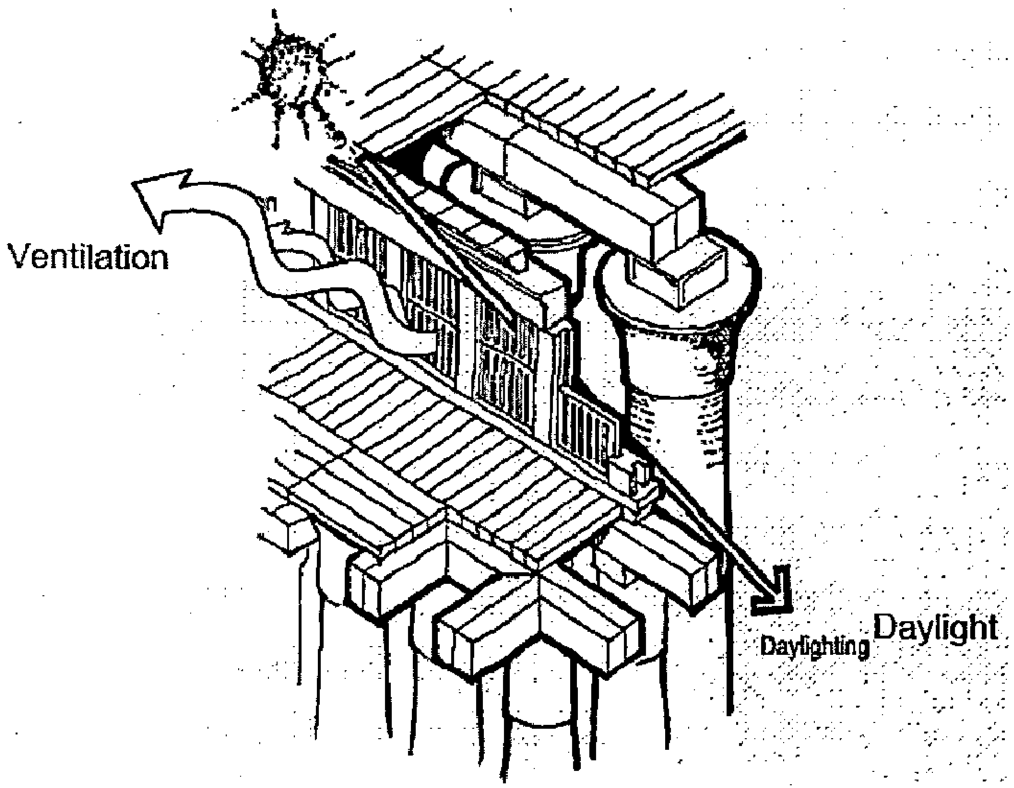


Figure 2.1 - Clerestory of the Hypostyle Hall of the Ammon temple, Karnak.

The Sumerians (Mesopotamia, 3000-2000 BC) are at the origin of several of the most outstanding human inventions, such as the wheel, the cuneiform writing or architectural concepts such as the vault. To avoid overheating, they covered roofs with about 1 meter of earth. But the load induced by the weight on the roof reduced its span, because palm-tree was used for the structure. Therefore, houses were narrow and long, which complicated their natural ventilation. Thus, the occupants' comfort was directly related to the structure. The evolution of this roof-terrace concept led to the famous suspended gardens of Babylon. They were located near wells, from which an astute system raised water to the roof construction for the irrigation of the gardens. Water evaporation reduced the ambient temperature and the roof cover reduced house overheating.

For many centuries, vernacular architecture has been seen as the product of an evolutionary process in which the most suitable forms have survived by designing comfortable architectural spaces that respect local climatic conditions. This principle was also adopted by Marcus Vitruvius Pollio (ca. 70- 25 BC), roman architect, in his famous *On Architecture*. In his book Vitruvius, which is dedicated to the conception of theatre, he provided solutions for the day lighting, the natural ventilation, the thermal comfort and the room acoustics aspects. Vitruvius proposed that '*the spaces remaining between the beams, over the pilasters and the columns, are left open for light in the intercolumniations*'. The natural ventilation and thermal comfort could be achieved by '*taking especial precaution that the forum be not exposed to the south; for when the sun fills the cavity of the theatre, the air confined in that compass being incapable of circulating, by its stoppage therein, is heated, and burns up, extracts, and diminishes the moisture of the body. On these accounts, those places where bad air abounds are to be avoided, and wholesome spots to be chosen*'. On the room acoustics side, Vitruvius stated '*on this account the ancient architects, following nature as their guide, and reflecting on the properties of the voice, regulated the true ascent of steps in a theatre, and contrived, by musical proportions and mathematical rules, whatever its effect might be on the stage, to make it fall on the ears of the audience in a clear and agreeable manner. Since in brazen or horn wind instruments, by a regulation of the genus, their tones are rendered as clear as those of stringed instruments, so by the application of the laws of harmony, the ancients discovered a method of increasing the power of the voice in a theatre*'. These concepts promoted by Vitruvius remained the chief reference on architectural matters until the Italian Renaissance.

Traditional Japanese and Korean houses are interesting examples of an architectural concept fulfilling several assignments simultaneously. The house walls consist of sliding doors made of wooden lattice panels covered with translucent rice paper as shown in Figure 2.2. During the hot and humid period, the facade may be widely open to invite the breeze. When the wind is too strong or too cold, the sliding doors are closed and the translucent paper still allows light to penetrate.

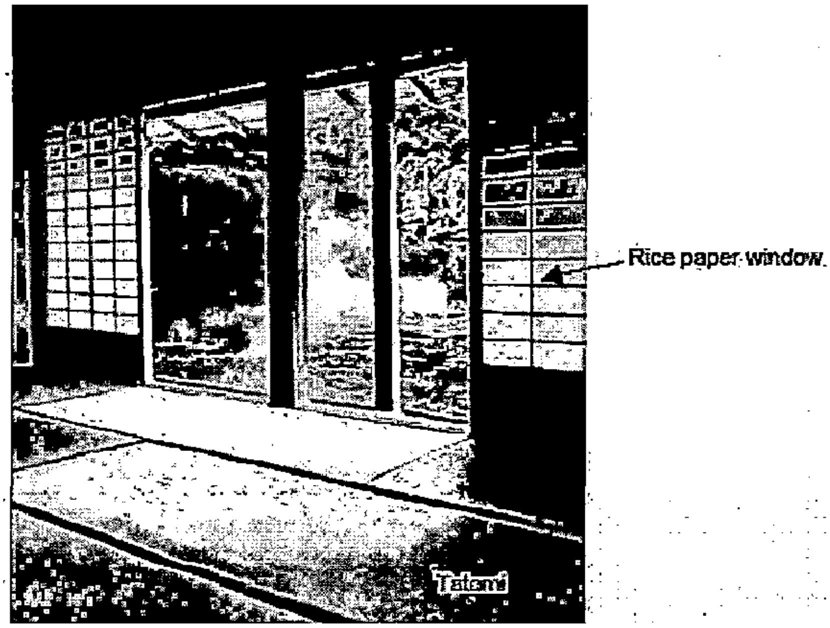


Figure 2.2 - Traditional Japanese house (Kyoto).

The most typical building element of that culture is probably the tatami mat floor, made of packed straw about 4 cm thick and famous for its standard size of about 90 cm x 180 cm which influences the dimensions of the entire house plan. Tatami and other porous materials have the particularity to absorb humidity, which improve the thermal comfort. Furthermore, the porous material increases sound absorption at high frequency and creates a good meditation environment.

The shading device of these traditional houses is made of a fine lattice of bamboo, as shown in Figure 2.3. Placed at the external edge of the eaves, it provides efficient solar protection as well as a shaded walking path and allows the air to flow through the lattice.

This type of construction is appropriate for hot and humid climates, which use native materials wherever possible to reduce the environmental impact of human presence on the surroundings. Traditional Japanese house design can be seen as an architectural representation of culture: '*natural rather than artificial, assimilating rather than conquering, simple rather than complicated, pure, rather than condensed, calm rather than vivid, reserved rather than proud*' according to Kimura.

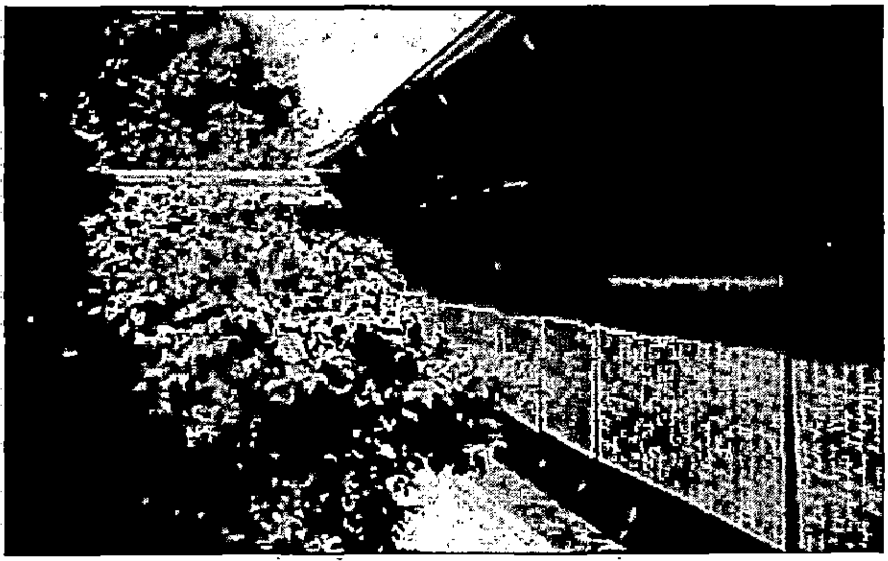


Figure 2.3 - Solar protection in traditional Japanese house, made of a fine bamboo lattice (Kyoto).

2.2 MOUCHARABIEH

Among all the solutions proposed by vernacular architecture, the most remarkable example of integration comes from the Arabian culture. The moucharabieh, which is a balcony closed by worked timber, was developed hundreds of years ago. At that time transport was limited and the use of imported raw materials was reduced. As timber is generally rare in hot climates, the system was made of a precise assembly of small timber waste.

The moucharabieh is made up of three distinct parts as shown in the left part of Figure 2.4. While its bottom part is opaque, its middle part, at eye height, is made of a close-mesh net, which admits fresh air. It is based on local materials and techniques and has also a cultural role in that it provides Muslim women with privacy without isolating them from the external environment. The upper part of the moucharabieh is made of a wide-mesh net that allows daylight penetration. A shading system reduces solar gains in summer but allows sufficient daylight to save oil for artificial lighting when the sun is low on the horizon (end of day or winter). The moucharabieh has another interesting application in a hot country. When porous pottery is placed just inside the moucharabieh, the air flows trough the apertures and cools down the liquid inside. This explains the name of the moucharabieh, derived from the Arabic *mashrabiyya* that comes from *Ma,* which means a temperate place and *Shrb,* which is a drink.

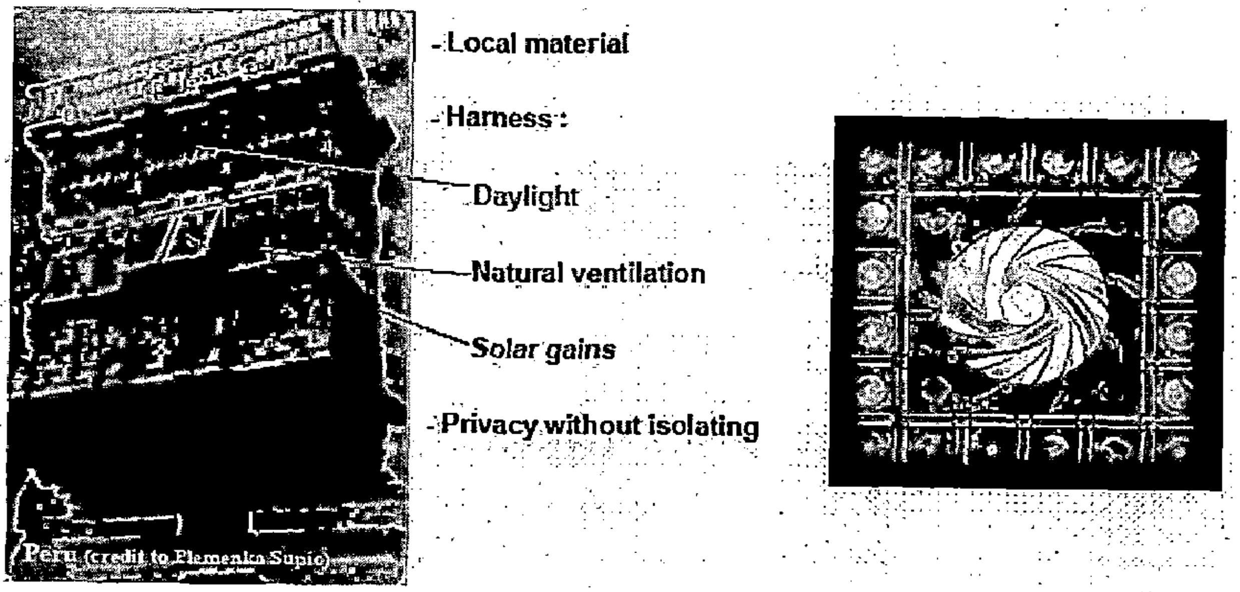


Figure 2.4 - Traditional moucharabieh (left) and a modern adaptation (right) at the Institute of Arabic World, Paris.

By using different locations and sizes of aperture, the moucharabieh provides in a simple way the possibility to control natural ventilation, harness solar energy and daylight, and to control the severe climate of hot countries. All this leads to a constructive balance between occupant requirements and environmental impact. The advantages of the concept have led to its widespread use around the world in hot and dry climates. The development of the moucharabieh took several decades, but is an example of vernacular architecture that meets multiple-domain requirements with just one building component. The moucharabieh can be regarded as the ancestor of the 'integrated and sustainable' facade solution that is promoted at present.

Recently, architectural developments tried to adapt the moucharabieh concept to fully glazed facades (Institute of Arabic World, Paris) as shown in the right part of Figure 2.4. The building is made of hundreds of mechanical apertures encapsulated in the glass facade and the size of the apertures is controlled by the quantity of solar radiation. The natural ventilation that was originally part of the moucharabieh has been replaced by an air conditioning system, although the French climate is cooler than the north-African climate. Unfortunately, the efficiency of the new system was not as outstanding as the traditional concept.

2.3 MODERN TIMES

Erecting impressive constructions with a good indoor climate has always been a complex challenge for architects, engineers and contractors. Since the beginning of modern times, the range of materials available in the construction industry market has widened considerably and new constructive principles have emerged in parallel. From about 15 at the beginning of the 20th century, the number of generic construction materials has grown to approximately 350. Technical developments permit independence from local climate, provide everybody with an acceptable indoor quality and have rolled back the limits of the architects' imagination; almost any imaginable concept can be developed.

Anon states in 1930 that '*building has evolved on the assumption that people who spend a considerable portion of their lives in offices may reasonably be expected to demand cleanliness, daylight, air, a reasonable internal temperature, adequate and decent sanitary accommodation, efficient lifts, artificial light and power...*'.

At that time, there were no standards that promoted the holistic approach. Nevertheless, there are several examples of architects who have successfully integrated functional demands and good building performance and delivered buildings with pleasant occupant comfort. Among others, the Solar Hemicycle House is an example of such an application of the multiple-view approach during building conception. Frank Lloyd Wright designed this two-storey house for Herbert and Katherine Jacobs in 1944 at Middleton, Wisconsin (USA). The distinctive design aspects of this house are its characteristic *C* shape, a fully glazed south facade, and its bermed backside as shown in Figure 2.5.

The South wall is made of floor-to-ceiling glass windows whose curved shape improve the efficiency of the facade in harnessing solar gains in winter when the sun travels from east to west. The roof has large eaves so that the south facade is protected from the direct sun radiation during the summer, and comes into the house in winter when the sun course is lower on the horizon, as shown in Figure 2.6.

Figure 2.5 Different views of the Hemicycle House.

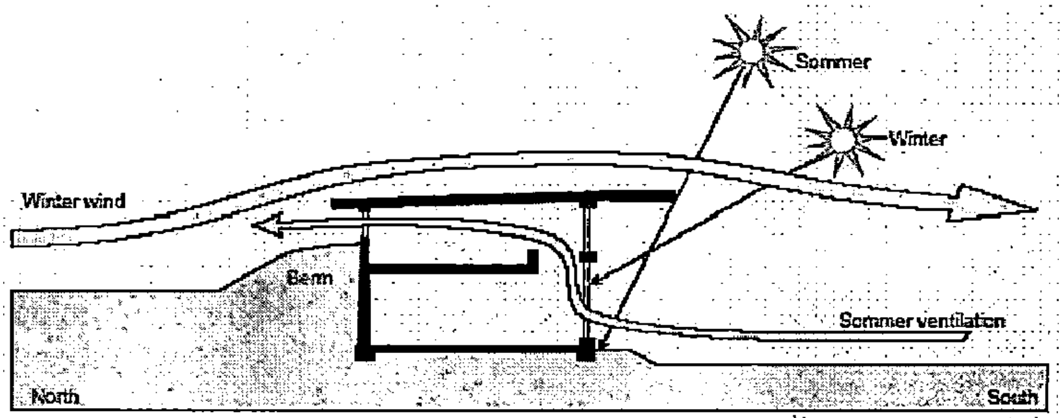


Figure 2.6 - Cross section of the Hemicycle House, showing the eaves efficiency, the principles of cross ventilation during the summer period and the protection against the northern wind.

The back wall goes up about 1.2 meter above the berm and has a strip of windows about 60 centimeters high which wraps all around the outer north facade of the house. The buried backside reduces the heat losses through the house envelope during the winter period and has a curved shape that increases the structure resistance to the pressure of the earth berm.

The building has a high thermal inertia thanks to the use of apparent limestone for the house structure, floor and walls. The irregularly laid of limestone bricks not only relate the building interior to the natural external environment but also increase the apparent surface of massive material for thermal storage purposes.

The second floor is a suspended balcony, whose front sits about 1.2 m back from the south window wall and allows heat to raise from downstairs to heat the upper floor during the winter heating season. During the summer, the backside (North) and the south windows are open to allow a cross ventilation of the house as shown in Figure 2.6. The combination of this natural ventilation and the high thermal inertia of the floor and walls provide a pleasant thermal comfort during the warm period. The windows are closed and the bermed facade acts as a windshield during wintertime, when there are dominant cold blows from the North. In combination with the *C* shape, they create a sheltered patio.

Finally, the use of native construction materials (limestone and pine) and a suitable application of the passive solar concepts entails that the Hemicycle House is a good example of a sustainable building providing good occupant comfort at low energy cost although it was erected thirty years before the 'oil shock'.

The holistic appraisal of the building performance as promoted by Anon or Wright was very limited at that time. Observations were made, but there were no standard requirements for building design. After the Second World War, standards mentioned timidly the necessity to ensure integrated occupant comfort in building design, such as the French *Règlement de la Construction, article 2*, in 1950's, which required taking into account acoustics and thermal insulation in buildings. But it was just a desired objective and no limit value was required. At that time Eichler seemed to be the first to scientifically analyze the concurrent improvement of thermal and acoustic performance ensuing from the use of facade insulation. This domain of research attained its pinnacle in the 1970's, when energy conservation and environmental considerations raised in importance due to the oil shock. The energy crisis served as a warning to the governments of the developed countries that oil energy is not inexhaustible and should not be wasted; and promoted the improvement of the building envelope insulation. For instance, Figure 2.7 shows three variants of a double facade typology. The left variant does not have any insulation, in the middle variant the air gap is filled with a mineral insulation of 5 cm, while the right variant uses 10 cm of insulation. For each variant the thermal and acoustics insulation are indicated. The thermal insulation is expressed by the thermal transmittance, known as the U-value, which gives the rate of heat loss through an element. The acoustic insulation is represented by the weighted apparent sound reduction index, which gives the sound level reduction obtained by the element. As can be seen in Figure 2.7, the filling of the air gap with a mineral insulation divides by a factor two the heat losses through the facade and improves the acoustics insulation by 3 [dB]. The thicker the insulation, the better the thermal and acoustics insulation.

During the oil crisis, several studies analyzed the concurrent improvement of thermal and acoustic performance ensuing from the generalization of facade insulation and the reduction of air leakage paths trough the external building shell, such as. These themes are still topical.

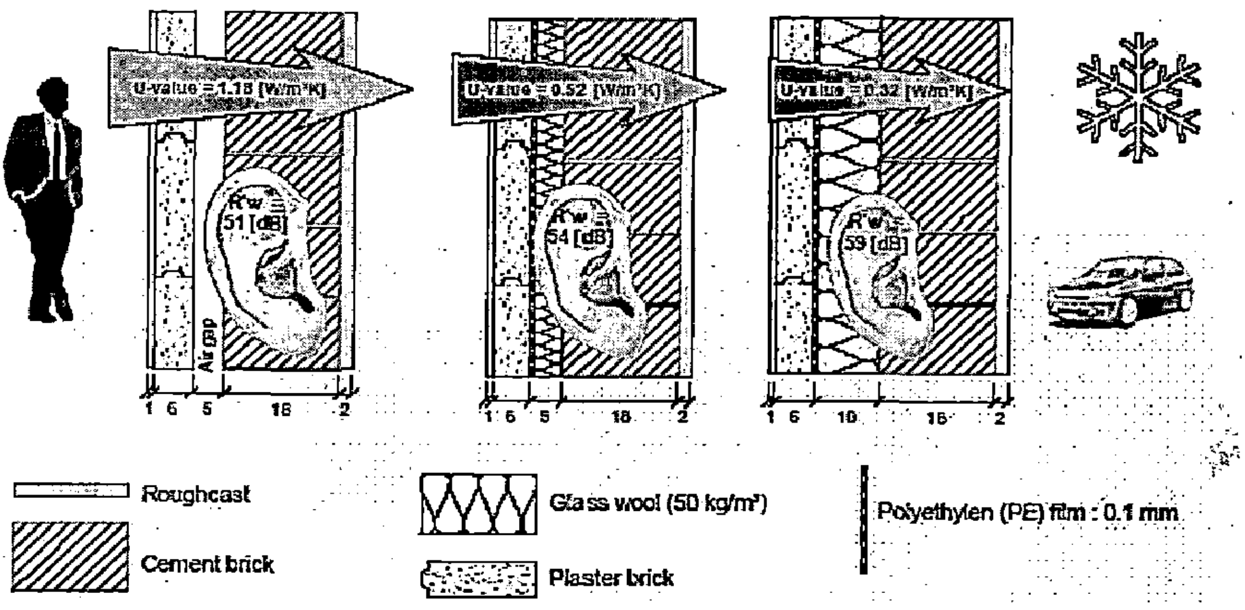


Figure 2.7 - Thermal and acoustics performance resulting from the use of mineral insulation.

Nevertheless, since the oil shock, i.e. in less than thirty years, the global energy production has increased by approximately 50 percent and tripled in the developed countries, in which fossil fuels represent 90 percent of the energy consumption. Efforts to reduce the environmental impact of buildings have focused primarily on efficiency in terms of energy consumption during the utilization phase. But if the ecological aspects of the construction are not explicitly taken into account during the conception stage, the retained solution will directly influence the environmental impacts generated by the building. In recent times, environmental concerns have also focused on environmental impacts generated by materials and processes (including transport), which must also be accounted as an environmental cost of the building construction. In the 1990's, the awareness of the human's activities on his environment regained attention. The impacts generated by the building during its whole life span were added to physical and financial considerations.

Among the building components, glazing probably assumes the largest number of functions simultaneously. It creates an acoustic and thermal protection with respect to the external environment, provides a view and natural ventilation, and allows the visible and solar radiation to penetrate into the building, which directly influences the heat loss and solar gains of the building. Although it took many years for human beings to define the best proportion of a window, adapted to the local climate and architectural traditions, a modern architect has the technical possibility to increase the window size until it occupies the totality of the envelope. For such buildings, a multiple-view assessment is important in order to reduce overheating and glare problems due to the solar gains.

Multiple-view assessment can be used as a commercial argument to put forward the advantages of a material and can also have surprising applications, such as the evaluation of thermal and visual comfort assessment of pavement used during foot drills. But the integrated assessment is an important issue, which is unavoidable in modern architecture and must be conscientiously followed; otherwise, unacceptable building performance may result.

2.4 CONSEQUENCE OF A NON-HOLISTIC APPROACH

Several recommendations already pointed out the importance of the integrated approach during the building conception, which require from the "architects *to co-ordinate sufficiently early, in relation with the global project, the lighting, air-conditioning and acoustic techniques*". The following example illustrates the consequences of having not simultaneously assessed the building's performance from different viewpoints.

Figure 2.8 shows the acoustic performance of an open-plan office room with a large glazed façade and a cooling ceiling where the thermal, ventilation and lighting systems were correctly appraised. As the room's acoustic performance during the design stage was not appraised, the low acoustic absorption of the cooling ceiling was not taken into account, which led to an excessive acoustic reverberation.

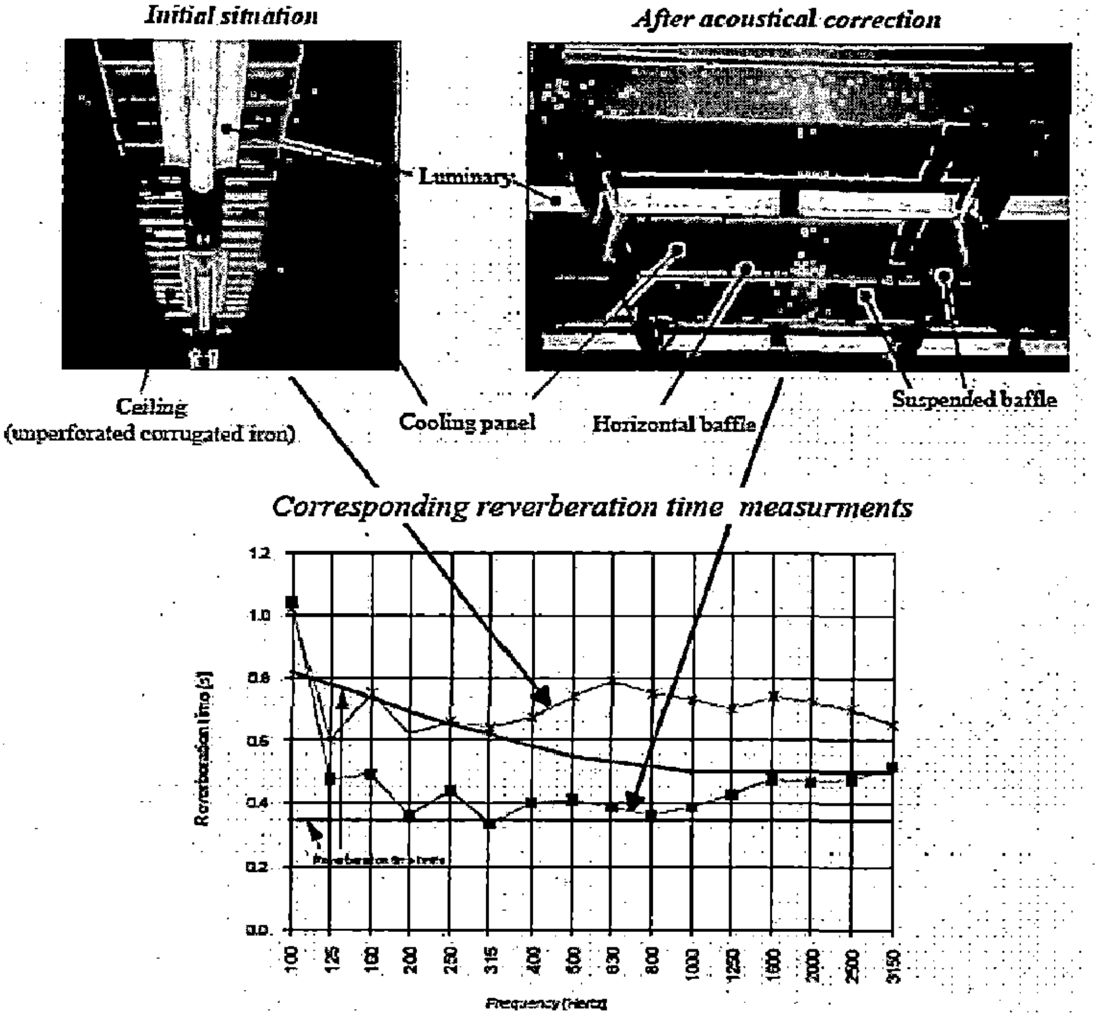


Figure 2.8 - Example where a room acoustics problem has occurred due to a lack of an integrated approach during the design stage.

The absence of an integrated approach necessitated a post occupancy acoustic correction. This correction had to reduce the reverberation time of the open-plan office without affecting the other systems. It had to provide a sufficient equivalent absorbing area without reducing the efficiency of the cooling ceiling and the desk illumination.. Replacing the initial system with a cooling suspended ceiling that integrated the luminaries and was perforated for acoustic purposes was financially not acceptable. Due to the office configuration, covering the walls with absorbent material was not possible because they were mainly transparent. The only remaining and also the most efficient location where the problem could be solved was the ceiling. The solution that was finally adopted using suspended baffles, whose dimensions and locations were chosen so that they would not affect the efficiency of the cooling radiant panels and artificial lighting system as shown in the right part of the Figure 2.8. This example illustrates the risk incurred by not adopting an integrated approach during the design phase, which can cause unacceptable performance that is generally difficult to resolve once the building is occupied, can be expensive in time and money and lead to a building environment that is not comfortable.

It is interesting to note that a similar problem was studied by Newman in the 1950's when excessive acoustic reverberation was shown to be due to the massive use of translucent acrylic ceilings used for artificial lighting. To meet acoustic and lighting needs, Newman proposed to replace acrylic panels with absorbent panels as shown in Figure 2.9.

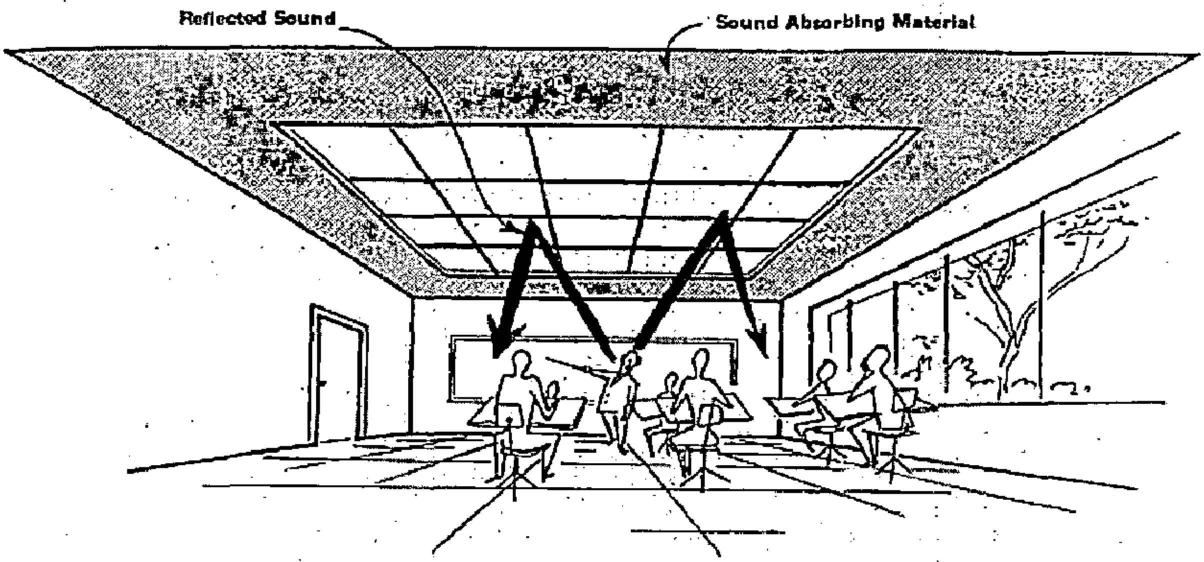


Figure 2.9 - Antinomy between acoustic reverberation and lighting performance by the massive use of acrylic ceilings in office buildings.

Whatever the building concept is, the design phase, during which the building's concept is defined, a site is selected and construction materials are chosen, has a major influence on the building performance that will determine user acceptance. An integrated approach is not only recommended for new building design, but can also be used to assess the performance of existing buildings.

In summary, this chapter has shown that through time, architecture has developed ingenious constructive solutions that could fulfill several assignments simultaneously. The limitation of available materials and construction processes was compensated by long experience leading to a constructive balance between occupant requirements and environmental impact. Technical developments and a sudden explosion of available construction materials during the 20th century have rolled back the limits of architects' imagination and they have now the ability to develop almost any imaginable concept. To meet the expectations of modern architecture, researchers have to develop complex and specific solutions. However, this complexity calls for an integrated appraisal of the building performance during the design phase to ensure a construction that meets with general acceptance. The next chapter presents a critical review of available solutions and describes the assignments of a multiple-view assessment.

CHAPTER 3

INTEGRATED APPROACH

At all times, the analysis of physical phenomena was dependent on technical developments and scientific knowledge. In the past, performance assessment relied on thumb rules and hand calculation. At present, the advent of building simulation programs has enabled non-trivial performance appraisals. The current generation of applications for the assessment of building performance ranges from simple spreadsheets based on simplified calculation methods to advanced programs, which allow the simulation of transient physical processes using complex numerical methods. In general, these programs deal, however, only with a small part of the overall problem.

Advanced architectural developments require an integrated approach to design. The domains of heating, lighting, ventilation and acoustics, for example, are often closely related and it is only by taking into account their interactions that a complete understanding of building behavior can be obtained. This chapter begins with a comparison of various methods developed to perform a multiple-view appraisal of building performance. The chapter follows with an analysis of the different simulation program types that support multiple-view assessment. Finally, the most common simulation tools available on the market are compared.

3.1 ASSESSMENT OF BUILDING PERFORMANCE

At present, building performance can be appraised using many different techniques:

- Scale model can be used when the physical phenomena are not scale dependent or if the loss of accuracy is acceptable compared to the studied parameters, such as for lighting and acoustics. Scale models are cheap and can be tested under real conditions. Under artificial conditions, experiments are reproductive, which facilitates variants comparison. But, measurement errors may originate from scale model effects, level of detail and material effects. Moreover, energy consumption and environmental impact assessment is not accessible on a scale model.

- Full-scale experimentation is probably the oldest method used to appraise a physical phenomenon and supplies incontestable information. It is appropriate to collect information when no mathematical model exists or to compare a mathematical model with in-situ measurements. The advantage of the experimental approach is that it deals with reality and therefore automatically includes simultaneous contributions when different phenomena are interacting; moreover errors are limited to experimental procedures. However, it is onerous and time consuming.
- Many physical phenomena are predictable with complex mathematical models. Under appropriate and acceptable assumptions, complex equations can be simplified with certain assumptions to provide analytical solutions, which show the degree of dependence between the parameters and the relative importance of the various terms. These analytical equations are simple but must be used within the assumption frame; otherwise it will lead to an erroneous analysis and inaccurate results.
- The emergence of pocket calculators and personal computers has made possible the numerical resolution of complex physical phenomena that do not have analytical solutions. The model implementation may be complex and may require a calibration/validation of the model, but the numerical approach simplifies the scrutiny of parametric analysis.

An integrated approach to building design requires a method to estimate the performance that will result from the interactions between the different domains. As can be seen from Table 3.1, which summarizes the capabilities of the available approaches, full scale experiments and numerical simulation are suitable methods for multiple-view analysis, because both integrate the complex physical phenomena and today they can address the same problem. As the experimental approach is time consuming and expensive, it can be argued that computer simulation is the preferred option for the integrated appraisal of design options.

Table 3.1 - Comparison of building physics simulation approaches.

Approach	Type	Advantage	Disadvantage
Experimental	Scale model	• Low cost • Reproductive experiment • Comparison of variants	• Scale effects • Model approximation/error • Measurement errors
	Full scale	• Complex phenomenon • Global analysis	• Time consuming • High cost • Measurement errors
Mathematical	Analytical	• Ease to use	• Simplified model
	Numerical (computer)	• Complex model • Fast calculation • Comparison of variants	• Request calibration/validation • Model might be complex • Model approximation/error

3.2 EVOLUTION OF INTEGRATED COMPUTER SIMULATION

Two thousand years ago, Vitruvius stated that plan, elevation and perspective were the basic representation for architects and the construction industry only used paper for building representation and information. The situation has considerably evolved with the emergence of pocket calculators and computers. Since the beginning, scientific results based on computer simulations were simplified and adapted to practitioner's needs, such as tables, diagrams or monograms, which deliver fast and sufficiently accurate results.

The ancestor of the actual computer-aided design (CAD) tools, Sketchpad, was developed in the early 60's by Sutherland to draft plans for interior spaces (see Figure 3.1). The idea was to use a graphical interface to directly enter engineering drawings into a computer. The idea was radical at the time, especially when you consider that computers at the time were only batch processing computers.

The idea of direct interaction with a computer was radical and supported the manipulation of objects using a light-pen, including grabbing objects, moving them, changing size, and using constraints. But this first generation of CAD programs cloaked their potential efficiency with complexity and slow speed of operation. They managed only geometrical information and could be considered as a digital mapping of the Vitruvius precept.

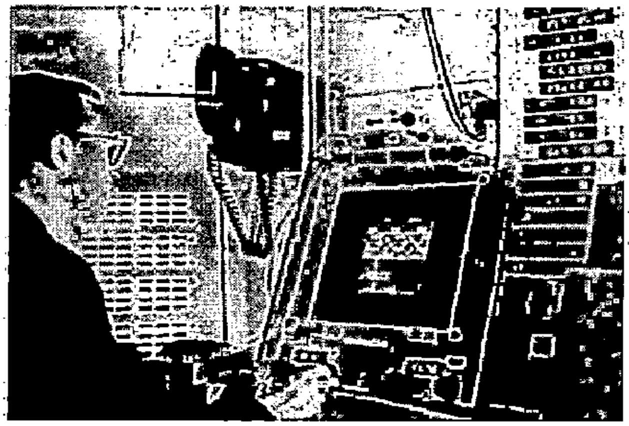


Figure 3.1 - The console of the Sketchpad Project, MIT, 1963.

During the 1970's, the computerized representation of a project evolved to provide a more complex building representation. It did not take long until developments in computer modeling pointed out the advantages of an integrated representation of the building. And also not long to recognize that if geometric information could be integrated, non geometric information could be integrated as well.

Since the early 80's, the development of communication and information technologies led to a growing awareness of the benefits that could be obtained if isolated programs had the possibility to communicate and exchange information. Barriers to the sharing and exchange of building data between computer applications had to be removed. Various interoperable applications were developed for the construction industry, mainly dedicated to time and cost planning. Several methods have been developed for a multiple-view simulation of building performance.

3.3 EXISTING APPROACHES FOR MULTIPLE-VIEW SIMULATION

From the viewpoint of simulation capability offered by simulation programs that perform a multiple-view assessment of building performance, four categories have been identified.

3.3.1 Stand-alone

Stand-alone programs are the most basic solution for a multiple-view simulation. In this approach several *unrelated* applications are used. This obliges the user to create one project model per application as shown in Figure 3.2.

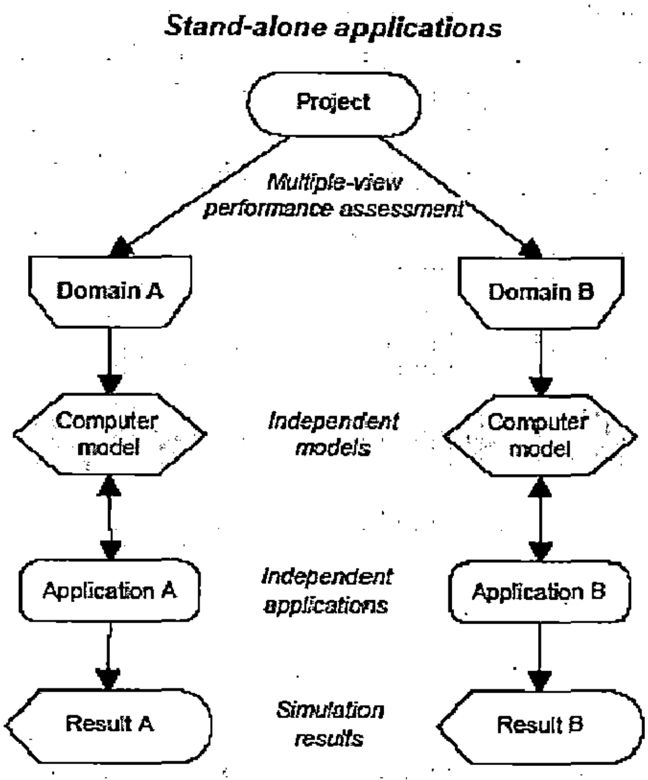


Figure 3.2 - Stand-alone approach for multiple-view simulation.

Creating different models of the same project has several disadvantages. It is time consuming. And any modification in the project has to be reported in different aspect models. In practice, a design change must be communicated to each member of the design team, who then must adapt his corresponding part of the model in order to assess the impact on his specific performance domain. Furthermore, some aspects of different views can require the same input. For example, to support an advanced room acoustic and daylight analysis of a room, a 3D model of the project will be required. If inter-application data transfer is not supported then two distinct geometrical models must be created. The stand-alone approach will then give rise to data redundancy and to potential inconsistency between models. Another limitation of this approach is that the user is required to master each program's interface.

3.3.2 Interoperable

Interoperable programs provide a procedure, whereby different computer applications can share or exchange one part or the whole building model. Each program is still used separately and has its own interface. The data model transfer is only possible at the application invocation level of the model, which does not allow an interactive data exchange during the simulation process itself. The following two approaches are possible:

Model Exchange: The stand-alone applications exchange the data model, as a whole or in part, by using a data exchange facility, based on a neutral file format, as shown in Figure 3.3.

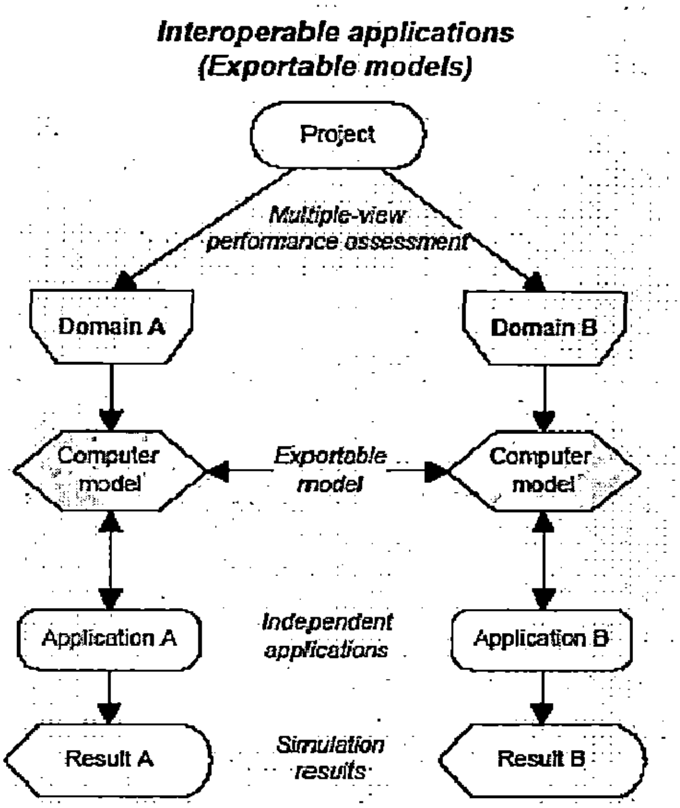


Figure 3.3 - Interoperable approach with model exchange for multiple-view simulation.

This exchange of information has the advantage of reducing the time and information required to set up the data model. Unfortunately, when the project is modified, each aspect- model might have to be updated as there is still one model per application, otherwise inconsistency will occur.

Model Sharing: View-specific applications are allowed in this case to extract the data required for their own purpose from a single data management system that holds a single model as shown in Figure 3.4.

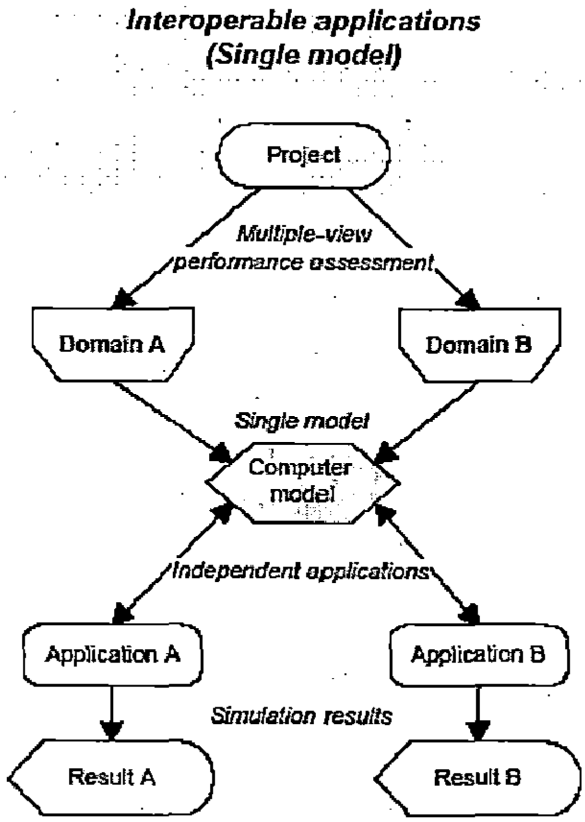


Figure 3.4 - Interoperable approach with model sharing for multiple-view simulation.

The advantage of sharing a single data model is to centralize the information in order to improve the information availability. It also simplifies model maintenance, but concurrent transactions management is an important and complex issue to solve.

The transfer of information can account for 80% or more of the resources required performing a multiple-view assessment of building performance and that the cost of the interoperable approach can be divided by about six compared to the stand-alone approach. The advantage of the interoperable approach is to support information exchange and sharing among partners, which leads to considerable time saving. Among the well-known simulation environments based on the interoperable approach are BDA, COMBINE, ECO-quantum, EQUER / COMFIE, IES-VE, RIUSKA, SEMPER and UO.

Allowing independent simulation programs to share/exchange data requires a specific data structure that can be used by the different programs, which has led to the definition of standard data models. Several neutral file formats are currently available. For instance, CAD tools generally support DXF and IGES neutral format. Although useful, these formats are limited to geometric entities and '*are an electronic version of annotated drawing, lacking in semantic depth*'. They do not allow the transfer of physical-related information to downstream applications. Currently, international institutions are working on the development and promotion of standard formats with geometry and physical content, such as STEP or IFC.

Although the interoperable approach may avoid data redundancy, it does not entirely prevent inconsistency and still requires a complex data management system. Furthermore, as with the standalone approach, the user is required to master each program's interface. Finally, it does not allow an interactive data exchange between applications during the simulation process itself. To overturn this weakness, a sequential data exchange can be provided, where the output extracted from one application is used as input in another application. For instance the lighting analysis package ADELINE can generate an output file of luminance data, which can be used as input by programs such as DOE-2 or TRNSYS to perform energy simulation. But when the physics between the views is tightly connected or when accurate simulation is required, the sequential exchange of data may not be applicable any more and a different approach is required.

The interoperable approach can be considered as a computer representation of the real interaction between the partners involved in a project, during which it is not rare that a specific concept has to be controlled by the different partners before its acceptance. This may lead to an iterative process of conception, control and correction as shown in Figure 3.5, which terminates when all parties agree with the final concept.

The interoperable approach can be seen as a digital mapping of an inter-partner working process. Within a real project, users would probably recognize that much time and effort is still required for information transactions (locate, translate, exchange, enter and update, check data), even if the interoperable approach may save time. The two following approaches provide a solution in which the computer is used in a more efficient way to simplify the multiple-assessment of the building performance by reducing the user interactions during the control process to the minimum.

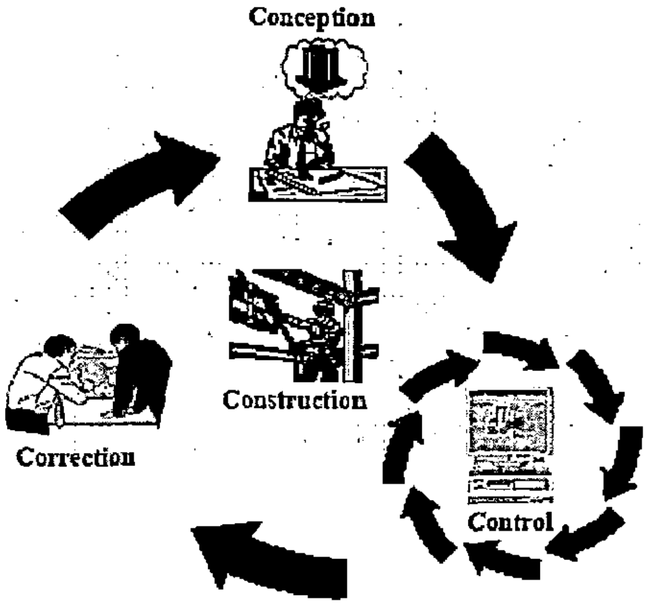


Figure 3.5 - The C4 process (Conception, Control, Correction and Construction).

3.3.3 Run-time coupling

Coupled (or linked) programs provide the facility to connect applications at run-time in order to exchange information in a co-operative way as shown in Figure 3.6.

Generally, one application controls the simulation procedure and requests the other application(s) when necessary. In this case, only the simulation engine of the coupled program(s) is required and the front-end interface corresponds to the driving application. A run-time coupling can be undertaken between the thermal/ventilation application ESP-r and the lighting application Radiance. Another example is coupling can be undertaken between the multi-zone airflow program COMIS and the energy program DOE-2. The main advantage of the coupled approach over the previously described simulation approaches is that it supports the exchange of information during simulation. But the coupled approach, as the interoperable approach, is limited by the maintenance of data and link consistency that depends on the separate evolution of each application.

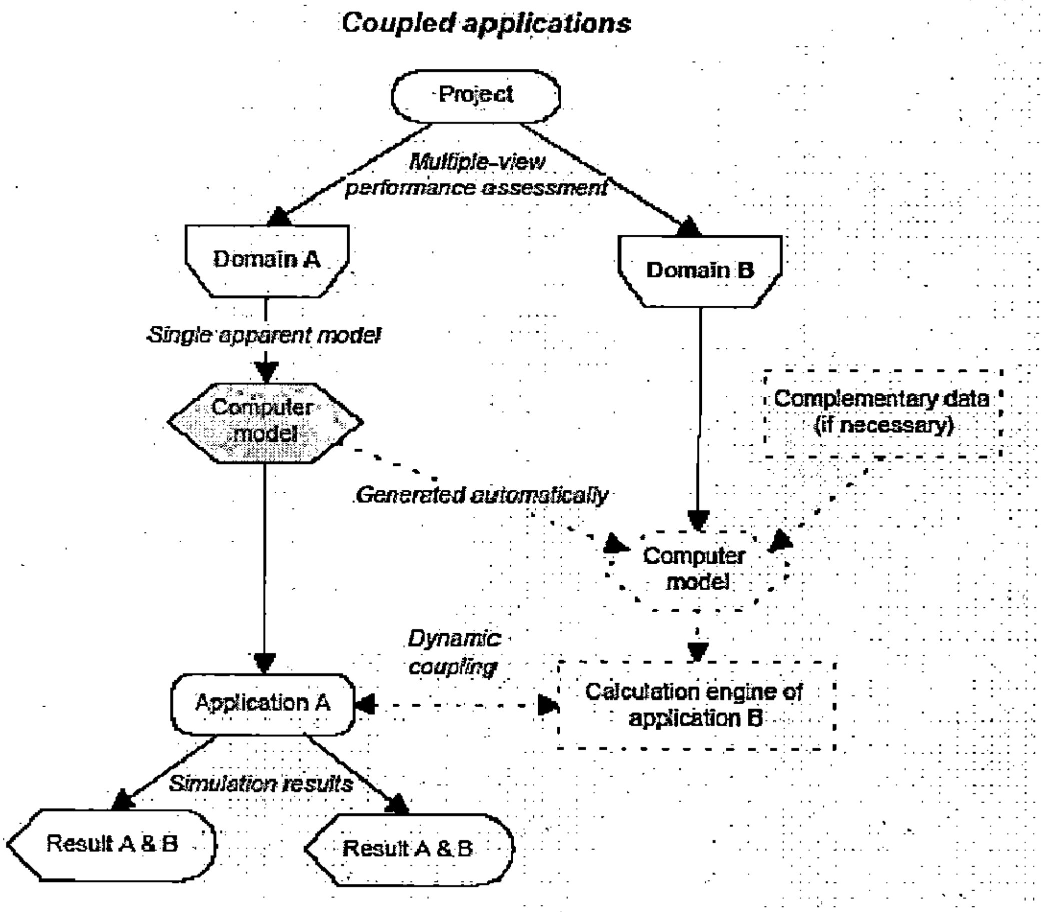


Figure 3.6 - Coupled approach for multiple-view simulation.

3.3.4 Integrated

Integrated programs provide a facility to simulate different views within the same program as shown in Figure 3.7.

As in the run-time coupling approach, a truly integrated simulation relies on the information exchange throughout the simulation to resolve a set of combined equations that represents the driving process of simultaneously occurring physical phenomena. The aim of an integrated approach is to preserve the integrity of the entire building system by simultaneously processing all energy transport paths to a level of detail commensurate with the objectives of the problem to hand.

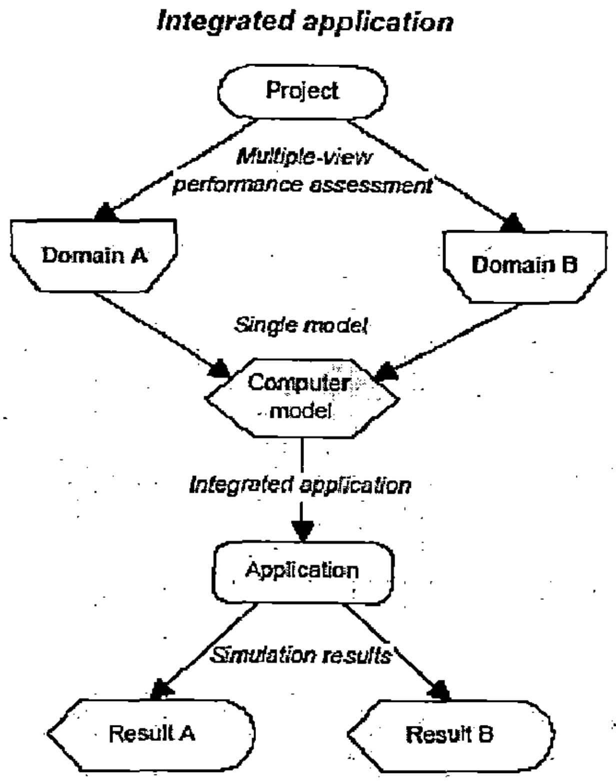


Figure 3.7 - Integrated approach in multiple-domain simulation.

Integrated applications can be obtained by extending the capabilities of a single application. Integration can also be achieved by merging into a single tool the best capabilities of existing applications such as done in the case of Energy Plus where the energy calculation core of DOE-2 and the ventilation calculation core of BLAST were merged at the algorithmic level.

Even where domains are not physically interacting, the integrated approach has several advantages. Firstly, the evolution of the application is made easier because it does not depend on external applications. As only one data model is needed to run a multiple-view assessment, data management is simplified. Changes can be made more easily and are better managed; verification becomes simpler, with all data for each element tied together. No exchange file format is required and modifications need only be implemented once. Finally, the fact that there is only one user interface eases the learning process.

Table 3.2 summarizes the possibilities offered by the four itemized approaches to a multiple-view assessment of building performance.

Table 3.2 - Comparison of multiple-view assessment methods.

Approach	Advantages	Disadvantages
Stand-alone	• Problem specific application	• Several data models • Several user interfaces • No dynamic data exchange
Interoperable	• Single data model • Model consistency	• Several user interfaces • No dynamic data exchange • Transaction management • Complete model if missing data
Run-time coupling	• Single data model • Model consistency • Single user interface • Dynamic data exchange • Physical model	• Link consistency maintenance
Integrated	• Single data model • Single user interface • Dynamic data exchange • Model consistency • Application maintenance	• Require knowledge in various domains

Only the coupled and the integrated approach can take into account the dynamic behavior of a building. The efficient development and use of an integrated application requires knowledge of the various views assessed and of constructive principles, as well as expertise in computer simulation. But once the physical model has been created, the integrated approach allows a flexible, simple and powerful multiple-view assessment of building performance.

3.4 AVAILABLE COUPLED OR INTEGRATED SIMULATION PROGRAMS

At present, several programs available on the market support integrated simulation, as summarized in Table 3.3; the assessment of a particular building performance view is graduated depending on the calculation methods used, ranging from 1 (simplified method) to 3 (advanced method). As can be seen, none of the available integrated applications can perform a multiple-assessment of the building intrinsic performance, the occupant comfort and the environmental impacts.

Table 3.3 - Comparison of the features offered by coupled or integrated applications available in the market.

Name	In-built drawing facility	Views							Approach	
		Energy	Ventilation	Equipment (HVAC)	Lighting	Acoustics	Environmental impact	Comfort†	Coupled	Integrated
BUS++'97		3	3					I		✓
Bsim2000 (Tsbi5)	✓	3			1				✓	✓
EcoPro		2					3			✓
EnergyPlus		3	3	3	1 or 2			T		✓
ESP-r / Radiance	✓	3	3	3	1,2 or 3			T, V, I	✓	✓
TRNSYS		3	3	3						✓

†Comfort: T = Thermal; V= Visual, I = Indoor air quality ✓: property is included

The most appropriate method to take up the challenge of assessing the integrated performance of a building is computer simulation. Currently, the market offers several interoperable programs. The disadvantage of this mode of operation is the complexity of use and its potential for model inconsistency. This can best be overcome by an integrated simulation approach. Currently, there is no simulation program that can estimate energy consumption, comfort conditions and, in parallel, provide the appraisal of the environmental impact of the building throughout its whole life cycle. The remainder of this document details the solution developed to provide a generic approach to a multiple view assessment.

CHAPTER 4

INTEGRATED CASE STUDY

The previous chapters have described in detail the necessity, the elaboration of a data model that enables a multiple-view assessment of building performance. The present chapter is dedicated to the utilization of all the developments undertaken up-stream. It presents the overall performance obtained for an office building as predicted by ESP-r. The simulation results have been compared with measurements monitored in the building during the post-occupancy phase. This chapter does not have the pretension to validate the simulation, but rather analyses the conformity of the simulation results with the measurement results and to see if the integrated approach was applicable.

4.1 THE ENERGIE OUEST SUISSE BUILDING

The Energie Ouest Suisse (EOS) building is a four-story office building, constructed between 1994-1995 in the city centre of Lausanne in the southwestern part of Switzerland on the Geneva lake shore (Latitude 46.32 N, Longitude 64.48 E, altitude 492 m). It is situated on a sloping site with a southwest orientation and consists of two building blocks linked by an entrance platform on the ground floor as shown in Figure 4.1. The building comprises about 10 office rooms per floor (400 m^2 per floor), which corresponds to a total gross area of 5900 m^2. The majority of the office rooms are located along the main building facade.

External light shelves are installed above a row of windows for office rooms located on the south facade as shown in Figure 4.2. The design of the light shelves was carefully studied before building construction, with the aim of optimizing their geometry (slanting angle) and their photometry (type of material and specularity) by means of scale model simulation. Finally, a central atrium is located behind the office rooms and provides them with daylight from the back.

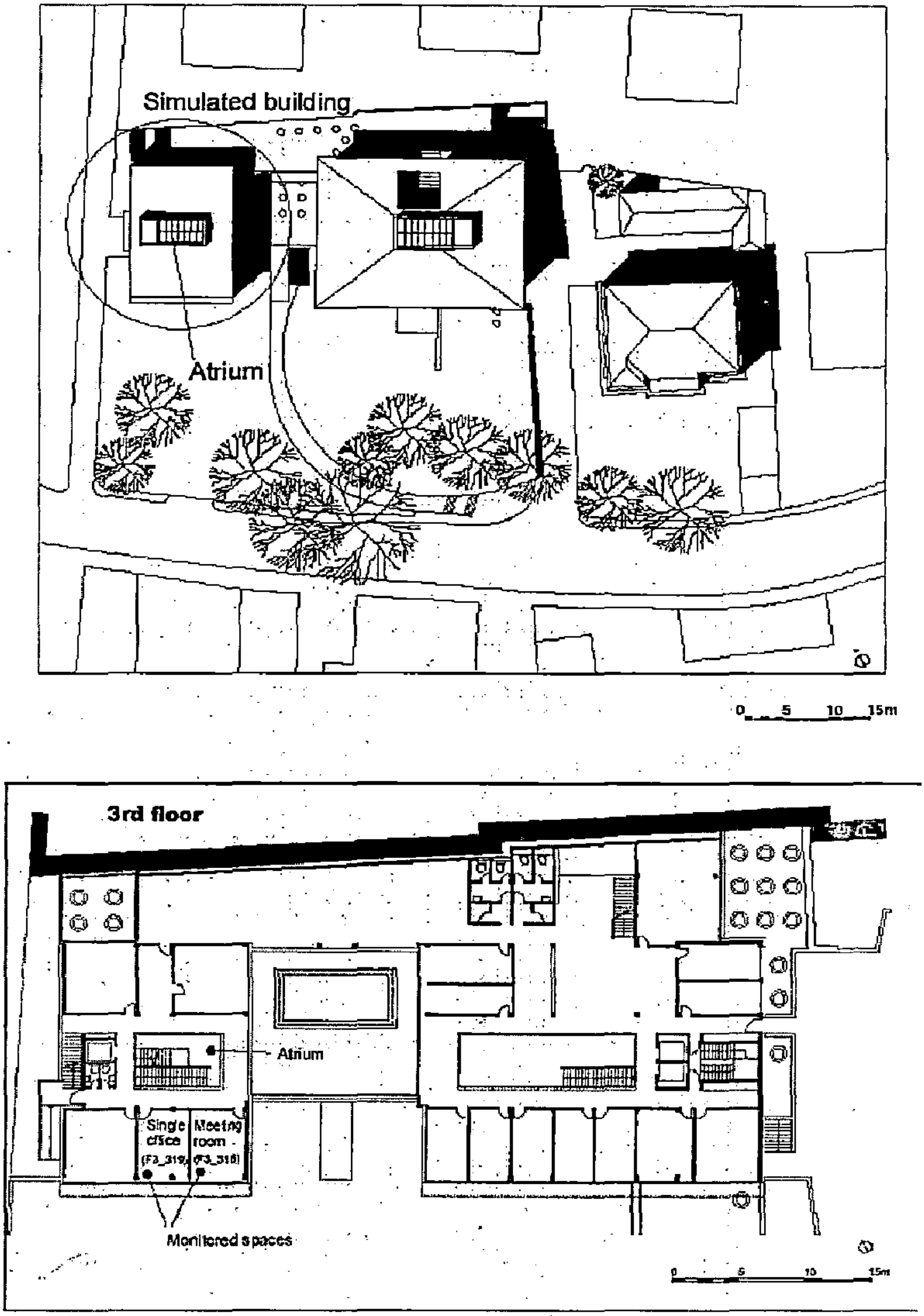


Figure 4.1 - Plans of the EOS building.

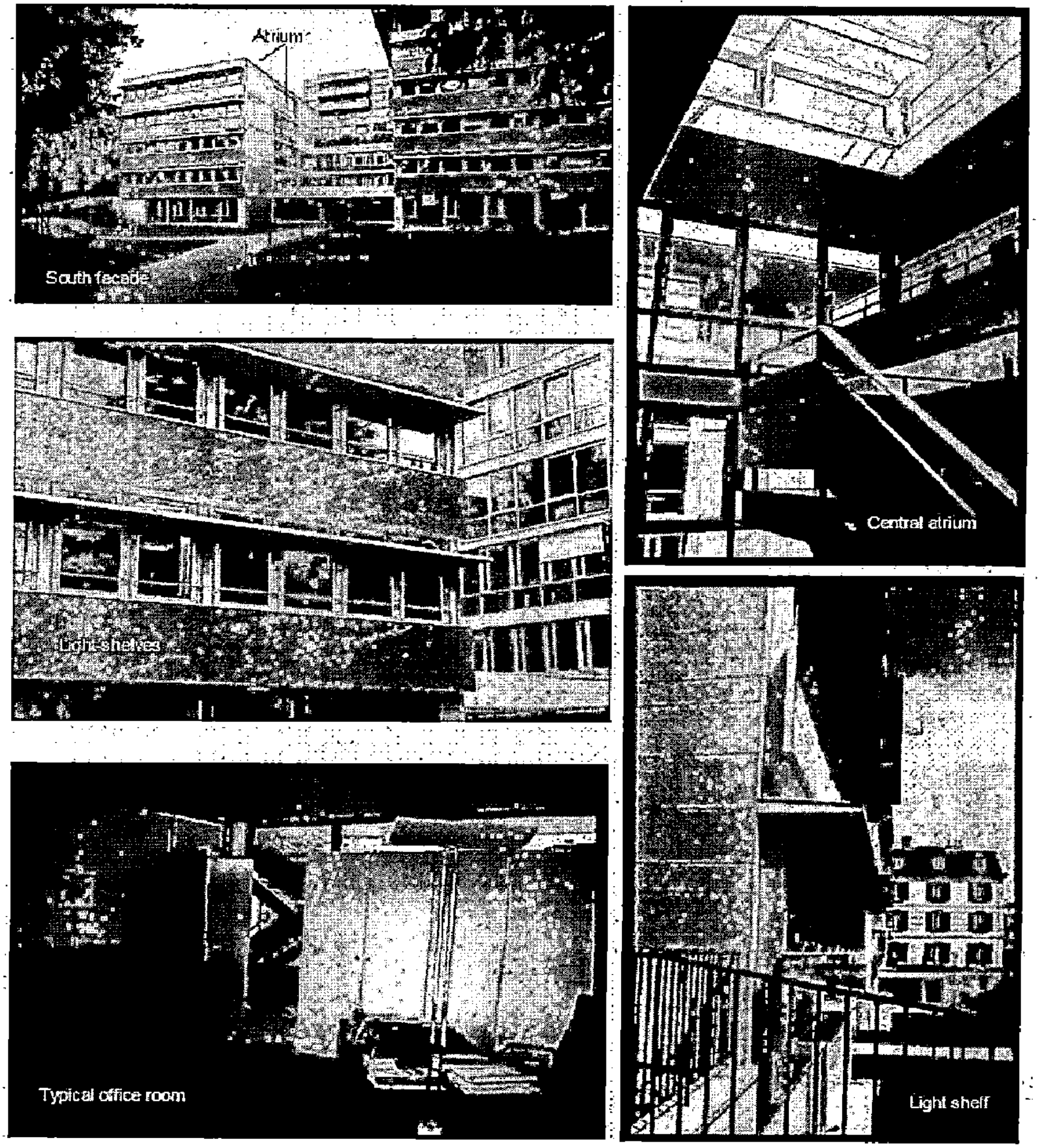


Figure 4.2 - Different views of the EOS building.

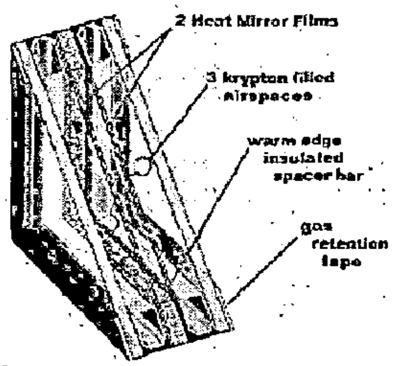
4.2 ROOM DESCRIPTION

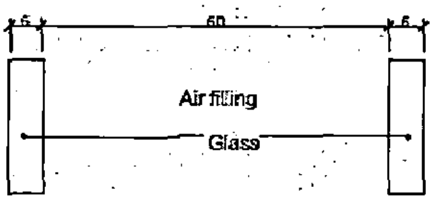
Each office room is occupied by one person, and has a width of 5.7 m, a depth of 5.2 m and a height of 2.6 m. The floor is made of a 24 cm height plenum with a fitted carpet and the ceiling has been given a roughcast finish applied directly on the concrete slab in order to improve the thermal inertia. The partition walls are made of steel sheeted plasterboard with 5 cm mineral wool insulation. The office room is provided with daylight mainly from the facade openings, which have a glazing area of 4.4 m². In addition, an opening of 1.2 m² is located on the backside of the room, providing daylight to the room through the central atrium as shown in Figure 4.2. The glazing ratio of an office room is equal to 0.19; the main part of the glazing area is located on the main facade (4.4 m²).

4.2.1 Windows

The EOS building uses super-insulated glazing systems for the facade. They are made of double clear float panes filled with Krypton, with two low-emissivity ($\varepsilon = 0.14$) coating films tight in the gas gap (4/10/3/10/4 mm) as shown in Table 4.1.

Table 4.1 Glazing system of the EOS building.

<table>
<tr><th>Glazing components</th><th>Description</th></tr>
<tr><td>External glazing system


(Superglass.tif)</td><td>Superglass is made of two 4 mm clear float panes with two low-emissivity coated films of 0.5 mm tight between the panes and filled with Krypton.
Spacer: Aluminium
Shading: External fabric blind + Alu. light shelf
Frame: PVC (Polyvinyl chloride)</td></tr>
<tr><td>Internal glazing system (thickness in mm)


</td><td>Double insulated glazing composed of two clear float panes of 6 mm and an air gap of 60 mm.
Spacer: Aluminium
Shading: None
Frame: PVC (Polyvinyl chloride)</td></tr>
</table>

Table 4.2 - Optical and thermal properties of the glazing.

Properties	EOS glazing types	
	External (Facade)	Internal (back wall)
Layers thickness [mm]	4/10/3/10/4	6/60/6
Gas filling	Krypton	Air
Low emissivity film	2 films tight in gas	-
Film emissivity [-]	0.14	-
Glass emissivity [-]	0.84	0.84
Overall, normal incidence visible transmittance τ [-]	0.62	0.78
Overall, normal incidence solar transmittance g [-]	0.46	0.69
U-value [W/m²K]	0.77	2.85

The internal windows (between the office and the atrium) consist of double clear float glass (6/60/6 mm) filled with air. The glazed area of the back wall is small (1.2 m^2), which corresponds to a poor window fraction (0.09). The window has a PVC frame and aluminum spacer. An external fabric blind is used as a movable shading system for the facade window. Table 4.2 summarizes the overall thermo-optical performance of the glazing systems.

4.2.2 Artificial lighting

There are no lighting fixtures on the office ceiling. Each desk is equipped with a floor luminary in direct-indirect lighting mode. Each luminary uses 4 compact fluorescent lamps (4 x TL36 W). Switching between luminaries is possible from the entrance door and from the work desk. There is no dimming function on the luminary either daylight responsive or user controlled.

4.2.3 Ventilation / infiltration

There is no mechanical ventilation system in the office rooms. The building is naturally ventilated through transversal ventilation in the office and the openings located at the top of the central atrium. A large meeting room located in the core of the building is the only space equipped with a mechanical ventilation system, which is used only when the space is occupied.

4.3 COMPUTER MODEL

A detailed computer model was set up, which represented the last two floors of the southwest core of the building. The whole model consists of 21 interconnected thermal zones, as shown in Figure 4.3.

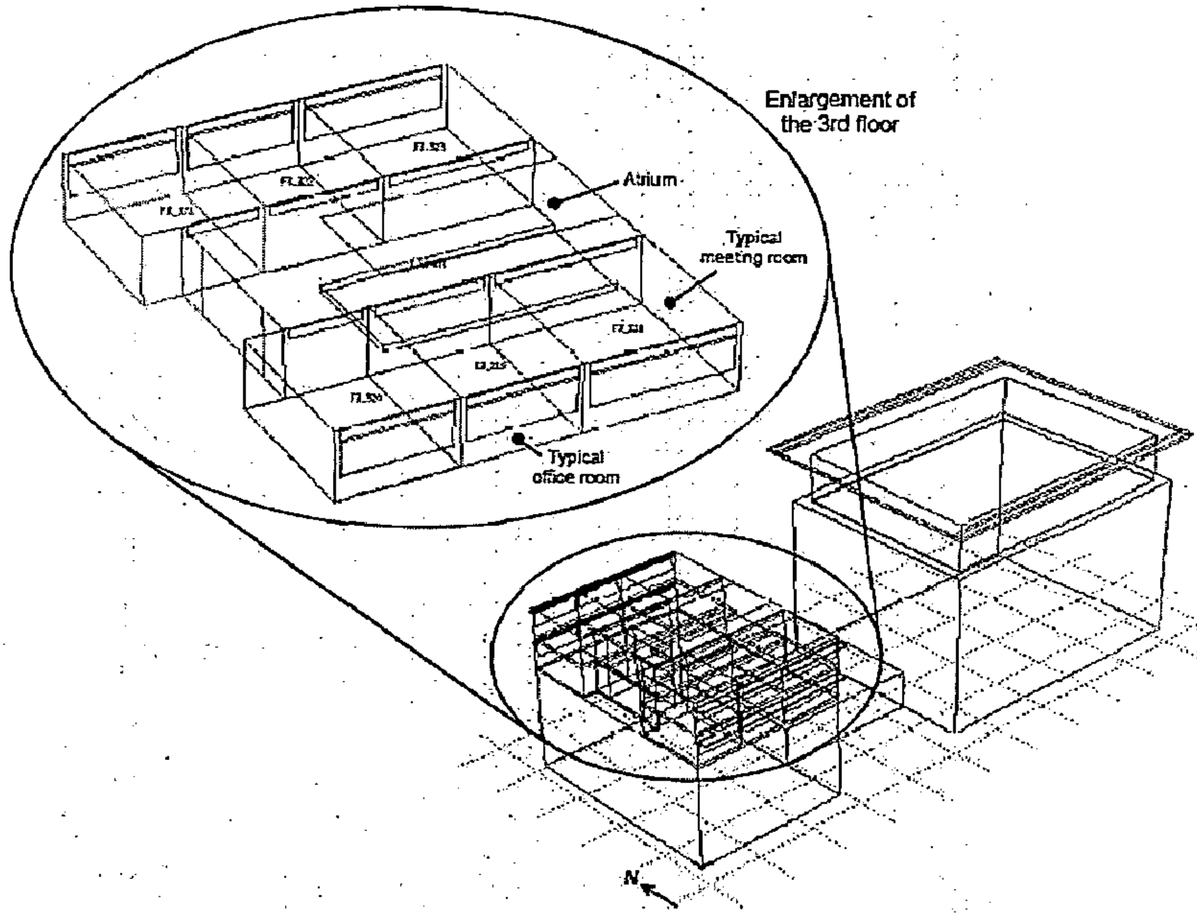


Figure 4.3 - Computer model representation of EOS building.

Eighteen zones are located on the second and third floor of the western part of the building. They correspond to the offices, circulation-atrium and the plenum floor. The remaining zones complete the building shape. A typical office situated on the third floor was selected for the daylight, room acoustic, thermal and visual comfort assessment and was monitored for this purpose. The third and fourth floor underwent an energy and environmental impact assessment.

4.3.1 Office rooms occupancy

It is assumed that offices are occupied by one person from 7 a.m. to 6 p.m. during weekdays. During the weekend and vacations, the room is not occupied. For the simulation, each office has an occupancy heat load of one person doing light work, which corresponds to 100 W of sensible heat and 40 W of latent heat.

4.3.2 Construction typologies

The opaque construction types presented in Figure 4.4 have been considered. It should be noted that the supporting bars of the plenum have not been explicitly represented, but have been included as a non-thermal layer in the construction to be accounted in the environmental impact assessment.

To improve the accuracy of the simulation, both external and internal glazing systems were explicitly modeled (each pane). On the other hand, the frame and spacer were not explicitly defined in the geometry model of the EOS building. The window area in the computer model corresponds to the transparent area of the window. This simplification is acceptable, as the frame does not impact significantly on the annual energy consumption, because its U-value is comparable to the U-value of the glazing system. However, the frame and spacer were included in the glazing constructions as a non-thermal layer, which means that they are accounted in the environmental impact calculation.

4.3.3 Heating

The building is equipped with a central gas heating plant, which provides heat to the whole building. The heat is distributed through water radiators, located in each office. The set-point temperature is 20 [°C] during the occupied period, and an 18 [°C] setback is applied during off-hour periods on weekdays and during the weekend.

4.3.4 Ventilation / Infiltration

No flow network was set up, but ventilation and infiltration was defined as a constant air change rate. A constant infiltration rate of 0.1 [h^{-1}] was assumed during the whole year in the office room. During the transient and summer period, an air change rate of 2 [h^{-1}] was assumed during the working hours and of 5 [h^{-1}] otherwise, to take into account the cross ventilation used for night cooling.

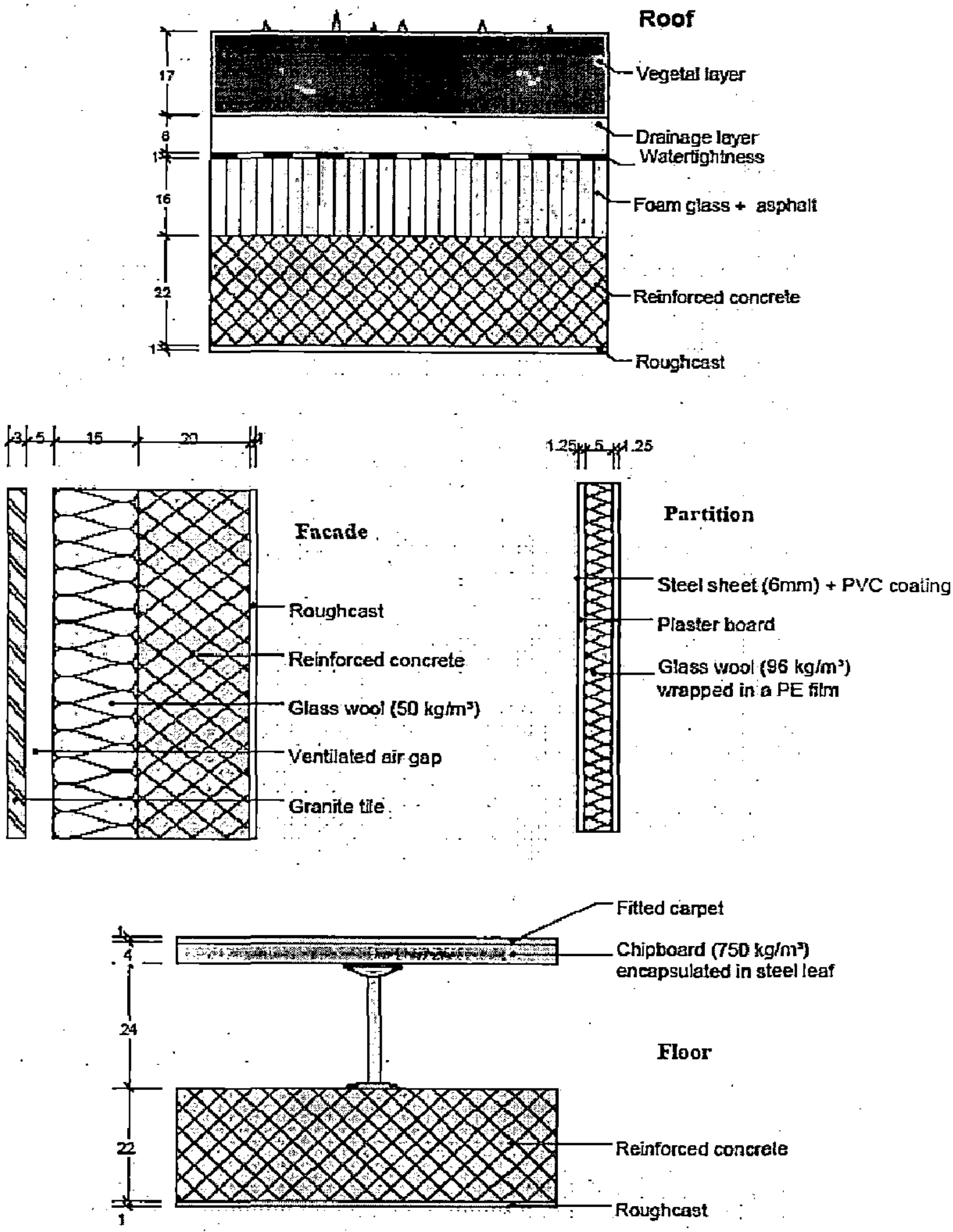


Figure 4.4 - Opaque constructions of the EOS building used in the ESP-r model (thickness in cm).

4.3.5 Artificial lighting

The office rooms have no ceiling lighting fixtures but are equipped with one floor luminary per working place, each one equipped with a (4 x 36) W compact fluorescent tubes with a 45% radiative and 55% convective heat gain. The luminary is at 3 meters from the window, near the working place. A hand switcher controls each luminary. As there was no dimming luminary, the artificial lighting simulation was performed with the daylight factor profile obtained from the daylight analysis. These data, as the visual comfort analysis, were assessed with the Radiance model generated by ESP-r. An on/off control strategy with a set point of 500 [lux] illuminance at the working place was assumed from 7 a.m. to 6 p.m. during the weekdays and nil otherwise, to simulate the occupant behavior..

4.3.6 Climate

Thermal simulation was carried out on the basis of an hourly time step simulation using the Lausanne climate retrieved from Test Reference Years (TRY). The corresponding extreme and average monthly temperatures are listed in Table 4.3.

Table 4.3 - Extreme and average monthly temperature for the Lausanne climate.

Temperature [°C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	11.1	11.9	17.2	17.9	26.3	28.7	31.8	32.8	29.1	19.4	14.5	13.2
Average	1.7	2.3	6.0	8.9	13.6	16.8	20.5	19.9	16.1	11.4	6.0	3.4
Minimum	-5.9	-7.6	-3.6	-2.7	2.3	7.6	12.1	9.9	7.0	4.7	0.9	-3.0

The annual energy consumption was extrapolated based on a dynamical simulation performed over three typical weeks, which are defined in Table 4.4.

Table 4.4 - The three typical periods of the Lausanne climate selected for use in simulation.

Period	Winter	Summer	Tansitory
Typical week	22nd to 28th January	10th to 16th July	9th to 15th April
Typical day	27th January	14th July	14th April

To select these weeks, the year was split into three different periods on the basis of degree-days (12/20 °C): winter, transient (spring and autumn) and summer. A typical week was selected for each period as representative of the climate throughout the period. The three weeks were chosen after analysis of the hourly weather data files on the basis of the solar radiation and ambient temperature. The annual energy consumption was extrapolated through weighting of the consumption of each typical week by the degree-days of the corresponding period.

4.4 ASSESSMENT OF THE BUILDING PERFORMANCE

Once established, the computer model was used for energy, lighting, room acoustics, environmental impacts and occupant comfort analysis. Building performance indicators were chosen in order to highlight the building domains listed in Table 4.5.

Table 4.5 - Domains and corresponding indicators assessed.

Domains	Indicators
Energy consumption	• Maximum power capacity • Annual energy consumption
Thermal comfort	• Predicted Percentage of Dissatisfied
Daylighting availability	• Daylight factor profile
Visual comfort	• Visual comfort index
Room acoustic	• Reverberation time.
Environmental impacts	• Emissions of pollutants related to energy consumption • Emissions of pollutants related to the building construction materials

To have the possibility to bring together and display the disparate performance metrics that result from the different simulation views and thus ease result interpretation and variants comparison, these performance metrics were grouped together in a synthetic reporting format. Integrated Performance View (IPV), which is a collection of relevant performance metrics for energy consumption, thermal and visual comfort, and environmental impacts generated during the operation phase, was used. The concept has been extended to include metrics related to the room acoustics and the environmental impacts of the building during its whole life cycle as shown in Figure 4.5. In the next sections, each performance indicator is analyzed separately and if monitored data are available, the results are compared to in-situ monitored data.

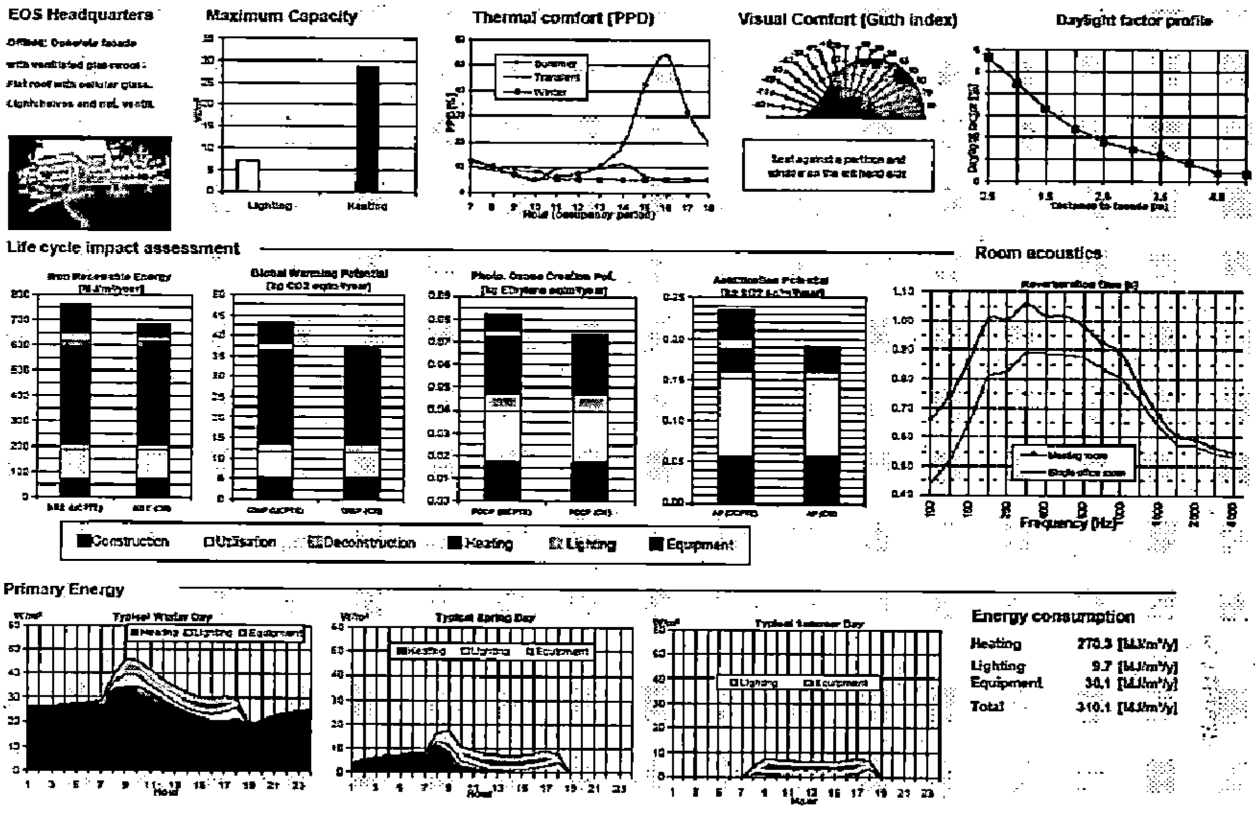


Figure 4.5 - Integrated Performance View of the EOS building.

4.5 ENERGY PERFORMANCE INDICATORS

The annual energy consumption for heating, lighting and equipment in the EOS building are listed in Table 4.6. The heating energy consumption of the EOS building is reasonable. This is not surprising when considering the solutions retained to reduce the heat loss through the shell and the absence of mechanical ventilation in most of the building. The heating energy consumption of the EOS building, averaged over the first three years of operation, is equal to 255 [MJ/m^2 y]), which corresponds to a difference of about 5% with the simulated results.

Table 4.6 - Normalized Performance Indicator of the EOS building.

Source	Fuel	Useful energy delivered		Monitored
		kWh/m²/y	MJ/m²/y	MJ/m²/y
Heating	Gas	75.1	270.3	250.6
Lighting	Electricity	2.7	9.7	42.5
Equipment	Electricity	8.4	30.1	

4.6 MAXIMUM POWER CAPACITY

The maximum power capacity of the building's technical installations is the maximum power required by the different energy appliances in the building, which for the EOS building corresponds to the lighting and heating equipment. The simulation returns a specific connected lighting power of 7.2 [W/m²], which is lower than the 9.4 [W/m²] that have been installed in the EOS building as shown in Figure 4.6. On the heating side, the EOS building is equipped with a gas boiler that supplies 39.3 [W/m²], which is not comparable to the 28.7 [W/m²] obtained by simulation. The differences in the lighting and thermal power capacity probably originate in the habit of lighting and heating engineers to overestimate the required maximum capacity by about thirty percent.

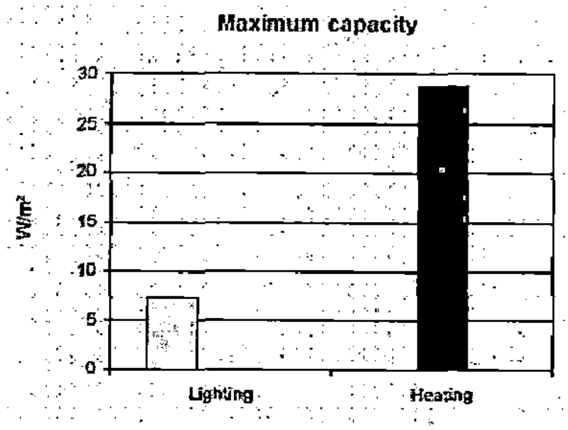


Figure 4.6 - Maximum power capacity for lighting and heating (EOS building).

4.7 PRIMARY ENERGY CONSUMPTION DURING TYPICAL DAYS

Hourly primary energy profiles for lighting, heating and cooling of the whole building are expressed as hourly profiles for each typical seasonal day, as shown in Figure 4.7. The peak demands for each typical day can also be retrieved from these profiles. As can be seen, it occurs at the beginning of the occupancy period. As the working hours pass, and the internal gains (energy generated by occupant(s), lighting and equipment) and the solar gains freely heat the office room, the required heating energy is reduced.

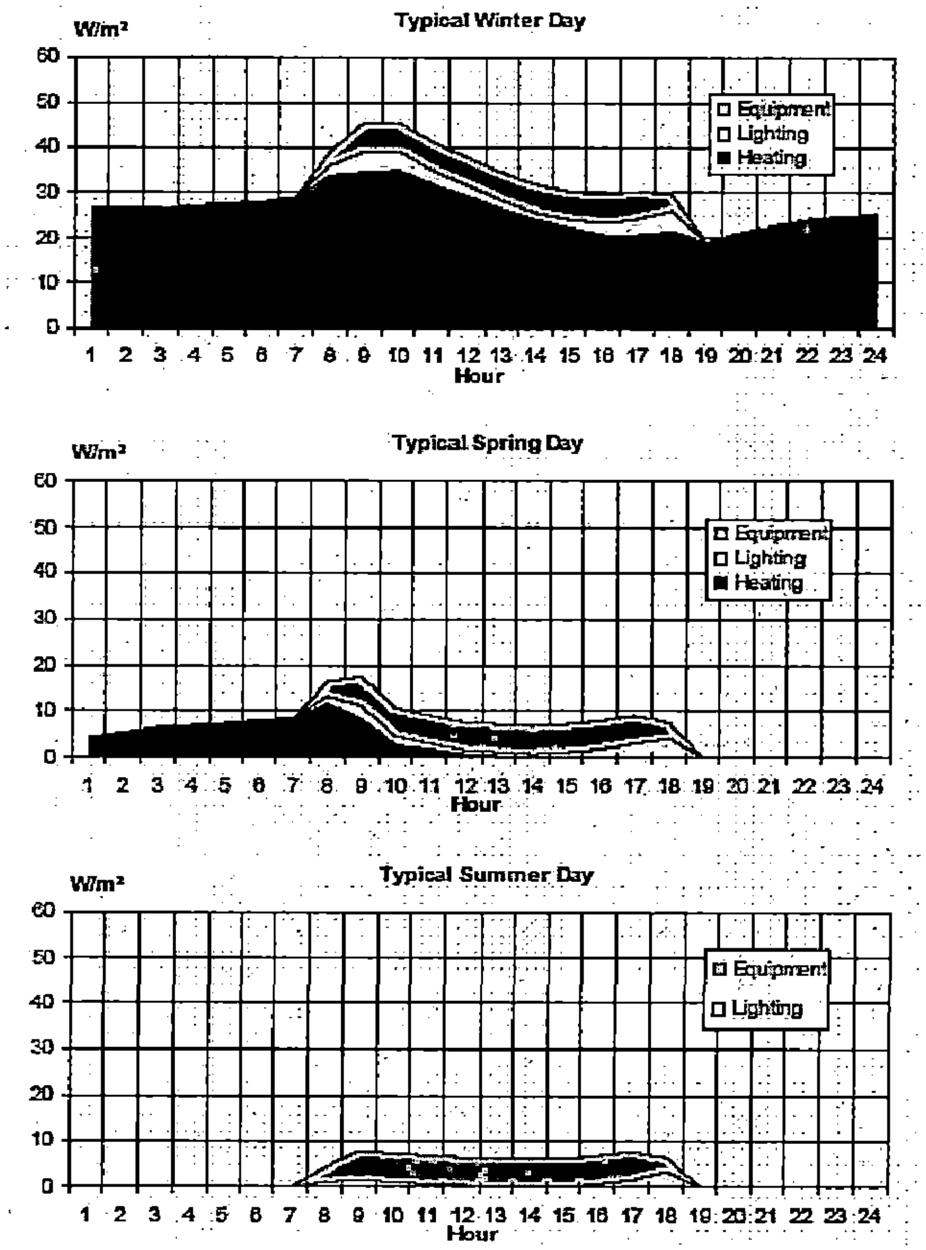


Figure 4.7 - Primary energy profile for three typical days (EOS building).

4.8 THERMAL COMFORT

The thermal comfort is expressed by the predicted percentage of dissatisfied (PPD) as defined in the ISO 7730 standard [ISO1994b]. The PPD gives the percentage of people likely to feel too hot or too cold in a given thermal environment. The PPD is influenced by the thermal properties of the room, such as the air and surfaces temperature, air humidity or wind velocity, but also by the clothing (thermal resistance) and activity (metabolic rate) of the occupant. In this study, it has been calculated in a south facing typical office room with the occupant clothing depending on the season and a metabolic rate corresponding to a sedentary activity as listed in Table 4.7.

Table 4.7 - Clothing and metabolic rate used to assess the thermal comfort in the typical office.

Season	Clothing [Clo]	Metabolic rate [Met]
Winter	1	1.2
Transient	0.85	1.2
Summer	0.5	1.2

The corresponding PPD in the typical office room during the occupancy period, for each typical seasonal day is given in Figure 4.8. The ISO standard recommends the PPD to be lower than 10% for an acceptable thermal comfort. But due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody and thus there are always a 5% of dissatisfied people whatever the thermal environment is.

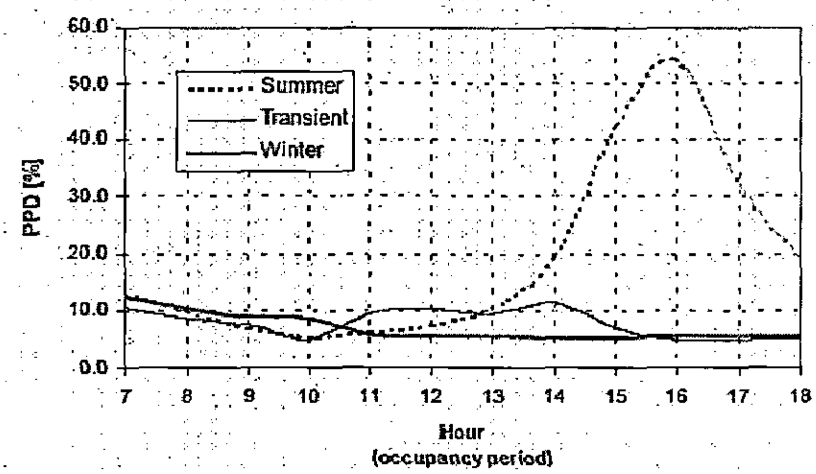


Figure 4.8 - Thermal comfort assessment in a typical office for three typical seasonal days.

During the winter and transient period, the thermal comfort is good as can be seen in Figure 4.8. During the summer period, the occupant experiences overheating at the end of the day, when the sun is low on the horizon (west). The light shelf of the typical office room (facing south) does not stop direct sun radiation. The external fabric blind is not sufficiently efficient to stop the direct sun radiation and the upper part of the external window is not equipped with a shading system, which leads to unacceptable solar gains in the office, which has a medium thermal inertia. A post occupancy evaluation of the EOS building, carried confirmed that one third experience overheating *often* and one third *sometimes* during the summer period.

4.9 DAYLIGHTING

The level and distribution of daylight factors (ratio between internal and external horizontal illuminance) has been used as an indicator of the impact of day lighting inside the building. A daylight factor profile is calculated for the representative office room. The profile is determined at the level of the work plane (0.75 m above the floor), perpendicularly to the window and in the middle of the room. The day lighting factors were measured under overcast skies according to the procedure recommended by the CIE. The daylight factor profiles of the monitored room and the corresponding simulation results are given in Figure 4.9. As can be observed, the computer simulation results are consistent with the in-situ measurements.

Compared to an office room without the light shelf, a more uniform illuminance distribution is achieved in the EOS office room, and thus lower luminance contrasts. The post-occupancy evaluation of the EOS building has confirmed the positive appreciation of the day lighting features of the building.

The DF of 0.5% in the rear of the office is comparable to the DF that would be obtained in the same office without the internal window. Therefore, this opening in the back wall does not contribute significantly to the illuminance in the rear of the office. This is due to the low glazing fraction of the opening and to the presence of the circulation of the upper storey, which plays the role of horizontal eaves and thus reduces the supply of daylight from the atrium.

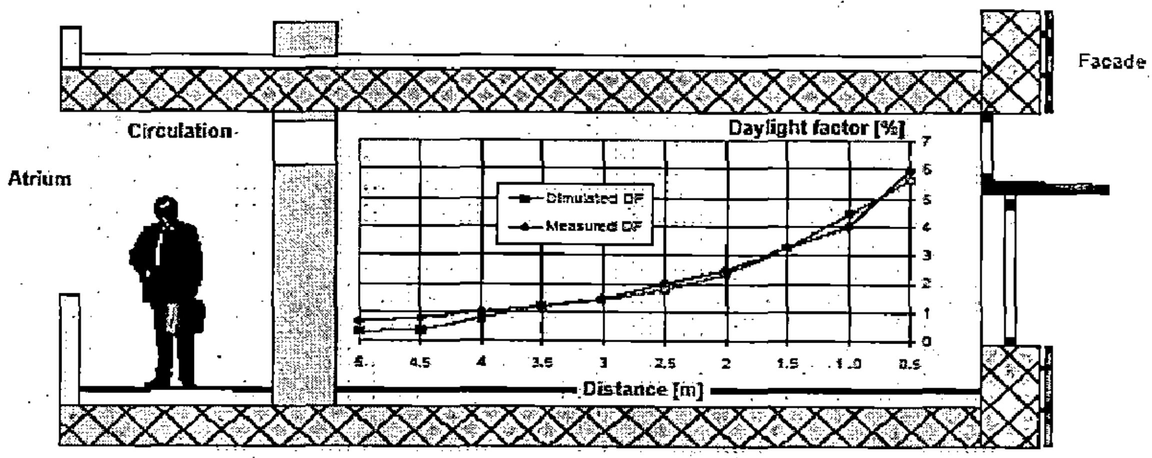


Figure 4.9 - Measured and simulated daylight factors (DF) distribution in a typical office room of the EOS building.

4.10 VISUAL COMFORT

The visual comfort has been estimated in a typical single office room. Among the different indicators that could be used, the J-index is probably the most suited to assess the visual comfort during a specific task (computer use, reading, etc.) and can be assessed with Radiance. Unfortunately, though, the use of that J-index requires the adding of a visual target in the geometry scene that is not yet automatically generated by ESP-r when it creates a Radiance model from its own model. Although the object could be added manually in the Radiance file, it has been decided to use another indicator that does not require manual completion of the Radiance model, to be consistent with the approach developed in this work.

Despite some limitation, the Visual Comfort Probability (VCP) has been selected because it has been widely accepted and corresponds to a conventional comfort appraisal, expressed through the percentage of persons satisfied by the visual environment when looking from a particular point of view in a given direction.

In the studied single office, the view position corresponds to the occupant seat, which is leaning with his back against the East partition. The VCP has been assessed with a view direction scanning from left (-90°) to right (90°) as shown in Figure 4.10. As can be seen, the VCP is below the recommended 70%, when the occupant looks in the direction of the facade, due to the glare sources generated by the openings. The more the view is oriented in the direction of the rear partition, the higher the VCP. A post-occupancy sounding out of opinion has confirmed that tendency. Some intense computer users have even partly obstructed the windows with an opaque screen to reduce the glare sources.

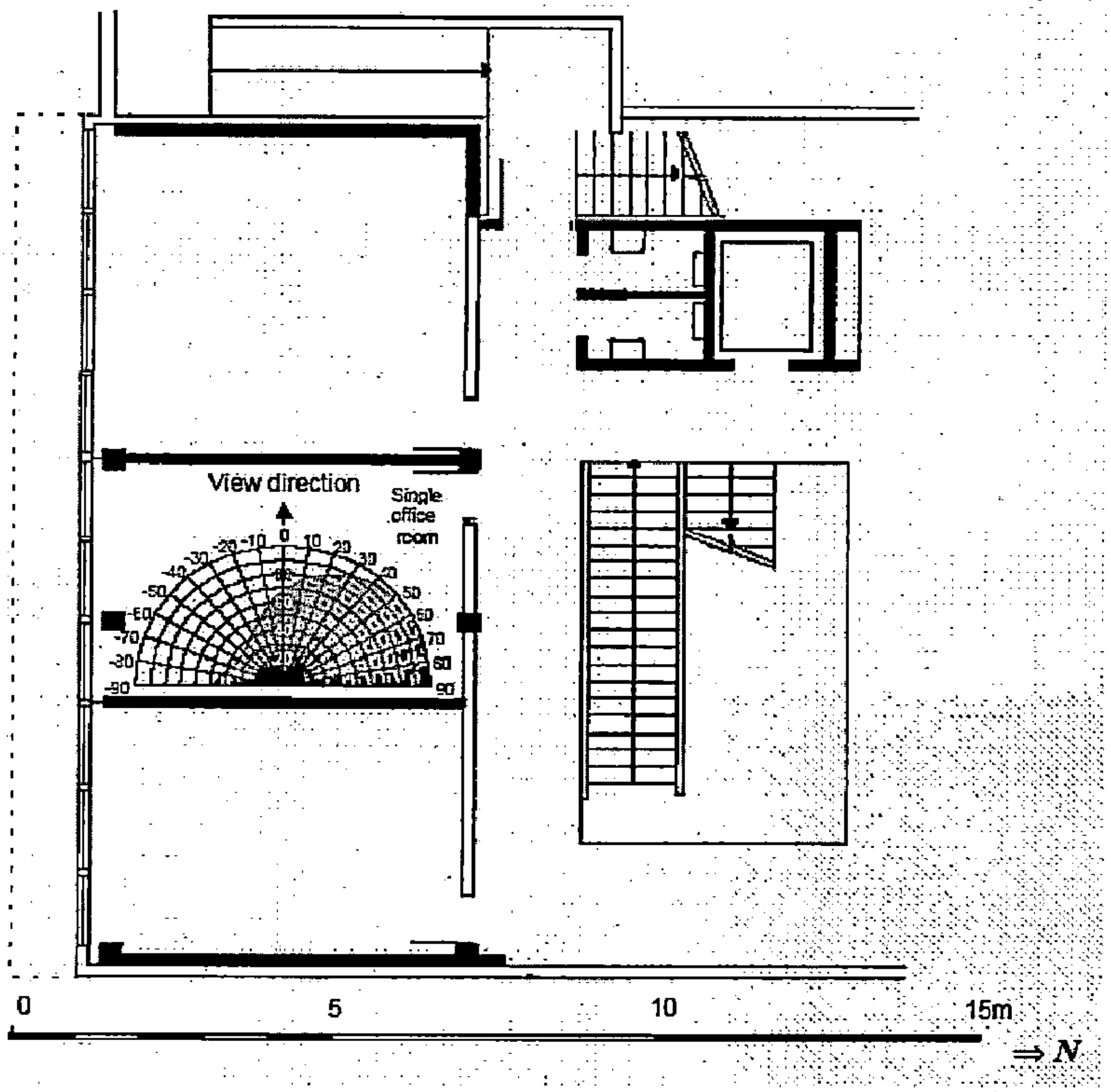


Figure 4.10 - Visual Comfort Probability (VCP) in a typical single office room.

4.11 ROOM ACOUSTICS

The reverberation time was calculated for the typical single office room and meeting room based on the Sabine, the Eyring and the Millington method. The monitored profile was established according to the procedure recommended by the ISO [ISO1975b]. These calculated and monitored profiles are included in Figure 4.11.

The monitored profile corresponds to the mean profile obtained by measurement at three different locations in the room and the error on the measured profile has been estimated as 10%.

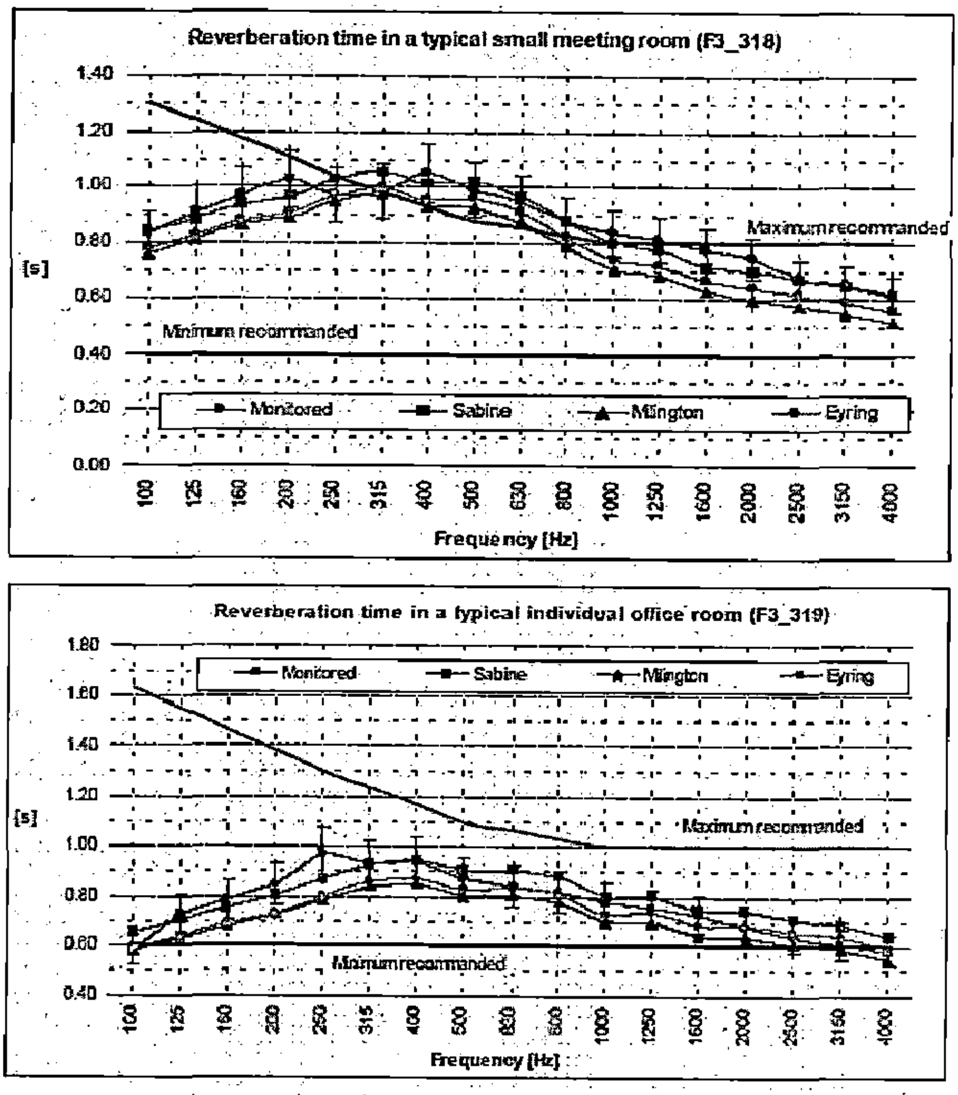


Figure 4.11 - Monitored and calculated reverberation time for a meeting room (top) and a individual office room (bottom) of the EOS building.

Figure 4.11 includes the recommended maximum and minimum reverberation time value. As can be seen, the reverberation time in the single office room is within the recommended domain. On the other hand, in the meeting room, the reverberation time is higher than the recommended value for frequencies between 250 & 1000 [Hz], which reduces the speech intelligibility as observed by the occupants. Among the three methods, Sabine has predicted the best results.

The reverberation time calculated in Figure 4.11 is representative for a zone air temperature of 26°C and a relative humidity of 60%, which correspond to the conditions observed during monitoring (summer day). To show the sensitivity to the room conditions of the air absorption at high frequency, Figure 4.12 displays simulated results obtained with the Sabine equation for two different periods of the year.

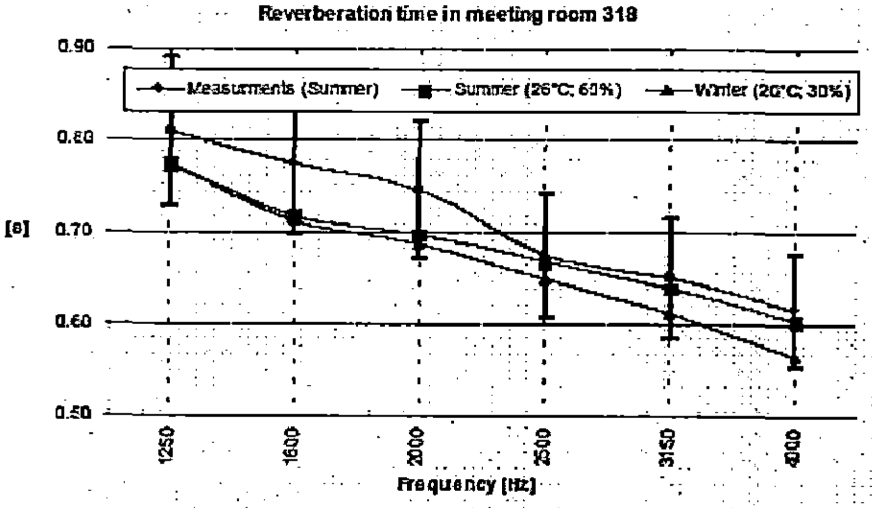


Figure 4.12 - Influence of the air temperature and humidity on the reverberation time (Sabine's equation).

Below 1600 [Hz], the reverberation time is not affected by the air properties and can be neglected, but above that frequency, the air absorption becomes relevant. In the case of the small meeting room (80m³) shown in Figure 4.12, the reverberation time difference between the two air thermo physical properties is about 8% at 4000 [Hz], which almost corresponds to the error range.

4.12 LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment of the EOS building presented in this section includes all the life cycle phases of all the materials defined in the eighteen zones that represent the second and third floor the building. It includes the intrinsic (building entity) and extrinsic (energy consumed for services) environmental impacts. The contributions to the intrinsic impacts are grouped into three major categories: construction, occupation, and deconstruction. The extrinsic contribution is segmented for each energy source consumed to provide the building services (heating, lighting and equipment).

For each indicator, the results are normalized per gross floor area and per year. The building life span was fixed to 80 years. To illustrate the impact difference according to the energy supply source, each indicator has two bin sets, one obtained with UCPTE-mix electricity (Euro) and the other with Swiss-mix electricity (CH) as shown in Figure 4.13. It emerges from the differentiation of the electricity origin, that environmental effects are lower with Swiss current because a major part of it is produced by hydraulic power plants. These results also show that when all the building phases are included in the impact assessment, the extrinsic and the intrinsic contributions are of the same order of magnitude.

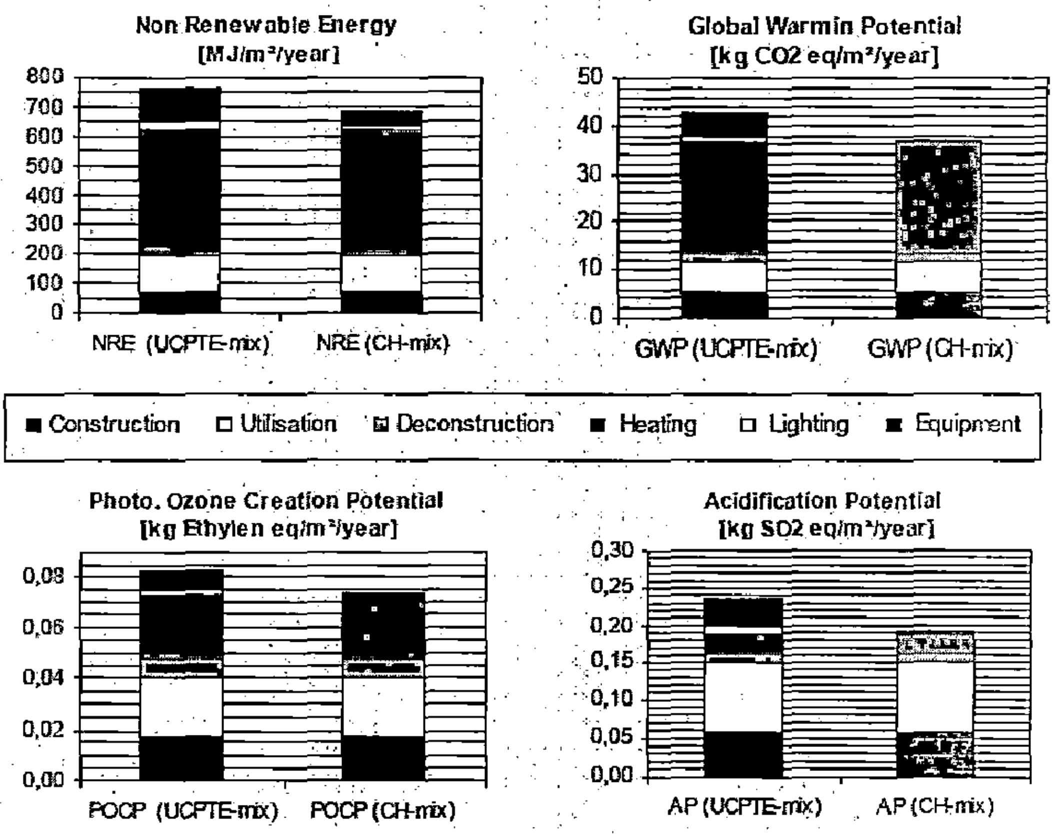


Figure 4.13 - Environmental effects of the EOS building.

Among the intrinsic environmental impacts, the largest contribution is generated during *Utilization*. This is not surprising as it encompasses maintenance and replacement (i.e. the sum of all downstream impacts generated by the replacement of a building element including its manufacturing, transport and assembly). During the building life span of the EOS building, all the construction materials except the reinforced concrete, is replaced at least once. For instance, the facade granite cladding is replaced only once, while the fitted carpet is replaced seven times. The sum of all the contributions generated for these material replacements is therefore not to be neglected.

As it can be seen in Figure 4.13, extrinsic contributions generate the major contribution of the NRE (73% for Euro and 70% for CH) and the GWP (69% for Euro and 64% for CH) for the EOS building. On the other hand, the intrinsic contributions generate the major contribution of the AP (68% for Euro and 84% for CH) and the POCP (58% for Euro and 65% for CH).

Compared to the other views, the LCIA assessment encounters more difficulty in gathering the necessary information. The availability of the environmental impact factors for construction materials, transport and material disposal is good. On the other hand, it was more difficult to obtain the material loss rate during transport and assembly, and the material elimination rate. This information was obtained from manufacturers and consultants, but a great variability has been observed depending on the sources. Nevertheless, comparison with other studies shows a good agreement of the results and therefore supports the assumption that the approach developed in this work is suitable for a comprehensive assessment of the environmental impacts generated during the building life.

CHAPTER 5

SIMULATION & THE DESIGN PROCESS

5.1 THE EVOLUTION OF BUILDINGS AND CHANGES IN THE BUILDING DESIGN PROCESS

5.1.1 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 under floor heating systems used by the Romans, where heat was provided in a way that increased the comfort perception of the occupants. Another example is cooling towers in arid regions such as in North Africa 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 is deep core buildings where rooms in the core location are lit by artificial light and ventilated by mechanical systems.

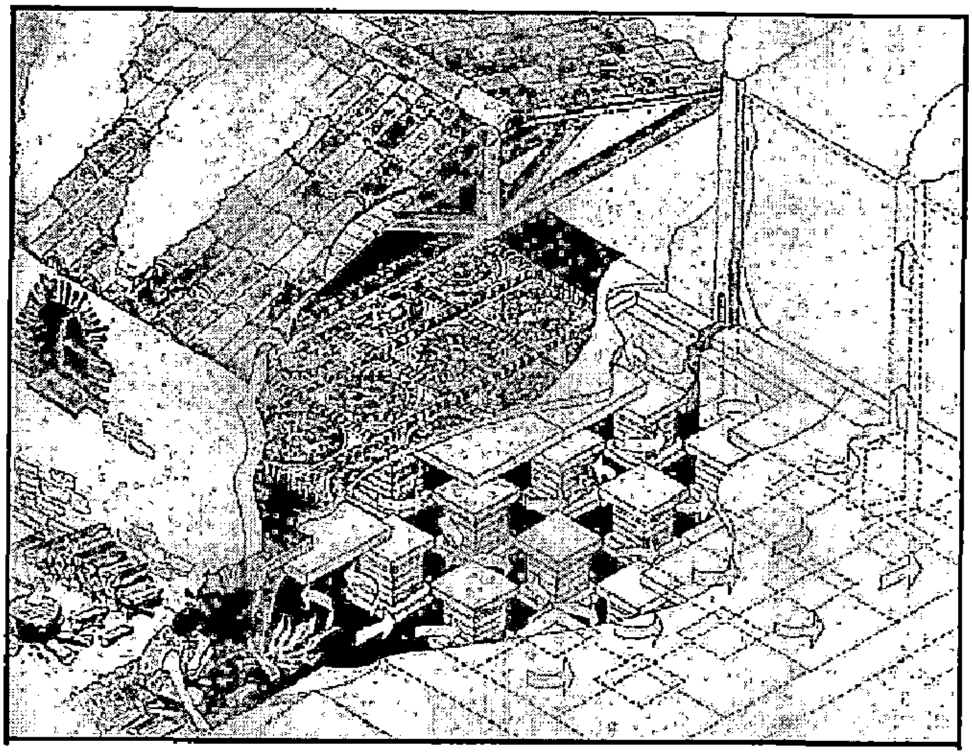


Figure 5.1 - A Roman under floor heating system

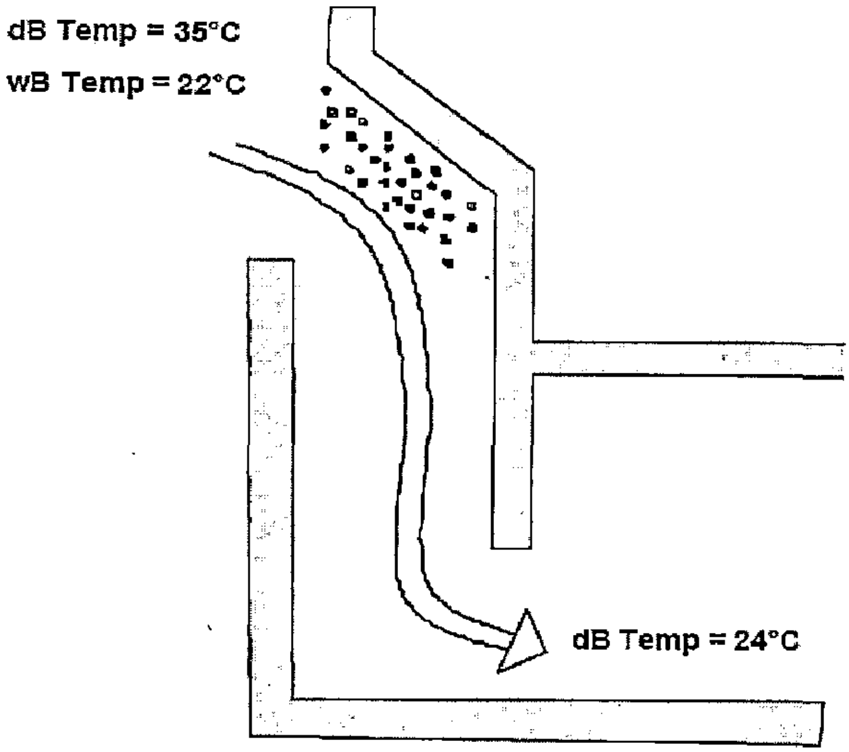


Figure 5.2 - Principle of a cooling tower for hot and dry climatic conditions

Three main building services inventions can be identified as having enabled such design:

- The invention of the light bulb
- Mechanical ventilation systems
- 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 in 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. 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.

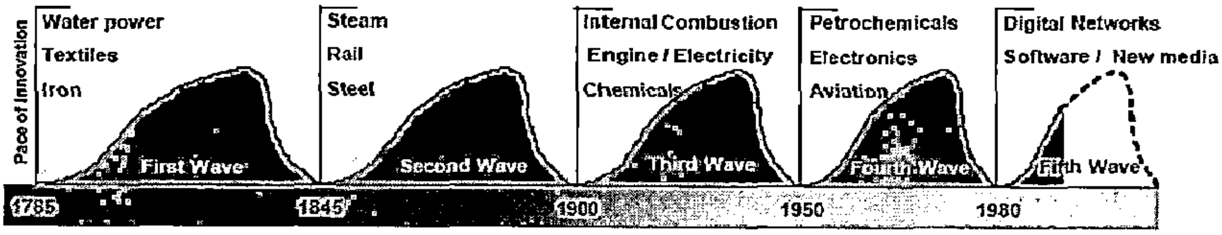


Figure 5.3 - The five waves of human technical development

5.1.2 Quality of contemporary buildings

Despite the fact that a new generation of buildings 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. In this respect, it is often said that designers of pre-modern buildings were much more capable of 'getting it right'.

5.1.3 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, 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). One may offer the examples of an igloo and a highland croft and point out that their design is a totally different proposition to the provision of housing in the noisy, congested city. It may be pointed 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 are 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.

To support the designer in decision making in this complex and multi-objective planning process Design Decision Support Systems (DDSS) have been developed 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.

5.2 OVERVIEW OF BUILDING SIMULATION

5.2.1 Evolution

Until the mid 1970s, simplified calculations were used to estimate the energy usage in buildings. 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.

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. This evolution from tools that are based on traditional calculation methods to contemporary simulation over four generations as outlined below.

1st 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.

3rd Generation: With advanced and more powerful personal computing facilities, 3^{rd} 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.

4th Generation: 4th generation program development started in the mid-nineties. This involved further domain integration, but also considered program interoperability, which is essentially a data modeling issue. In response to the growing uptake by practitioners, new developments emerged, including more accessible user interfaces, application quality control and user training. Air flow simulation is well integrated in 4th generation tools and is also commonly applied in the building design process.

The above section describes the development from traditional assessment methods to contemporary simulation software. It is evident that 1^{st} 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 2^{nd} and 3^{rd} generation programs, however, this is often at the expense of a complex software structure. In 4^{th} 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 5.4 depicts this process.

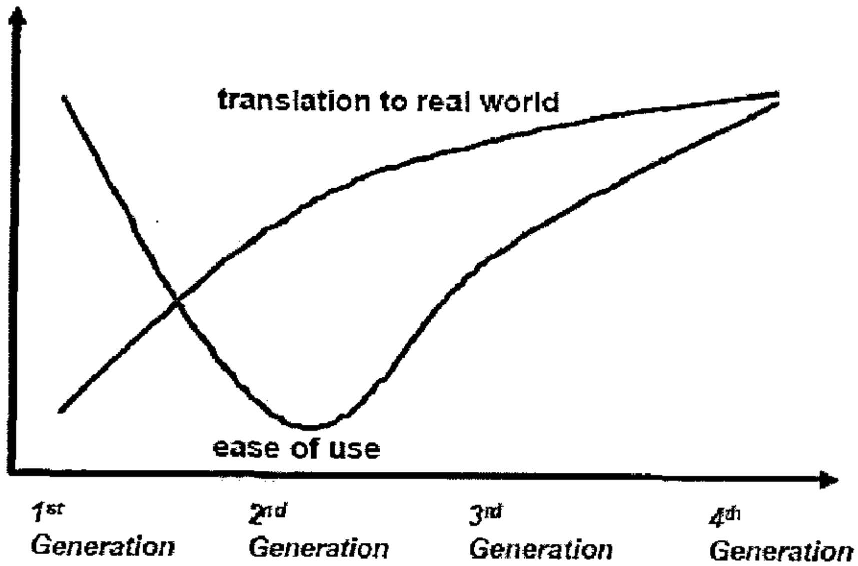


Figure 5.4 - Translation to real world and ease of use in simulation

However, the development of 4th generation simulation tools is not complete. 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.

5.2.2 Simulation capabilities

The previous section describes the evolution of dynamic building simulation towards a design process that will allow an integrated 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 and which has been under continuous evolution ever since.

The bases of each simulation model are polyhedral zones (see Figure 5.5) that are attributed with construction, internal heat gain and idealized 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 5.1).

From table 5.1 it can be seen that valuable information can already be gained from a simple attributed polyhedral zones (overheating assessment, visualization 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 idealized 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 (Computational Fluid Dynamic) analysis is more complex and requires from the user an understanding of the physical processes that are to be simulated.

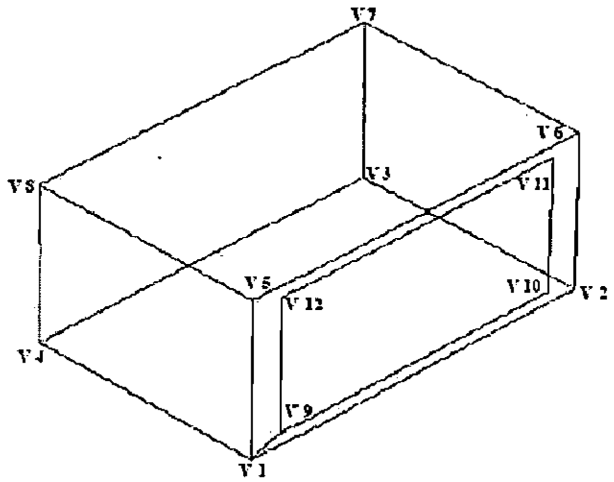


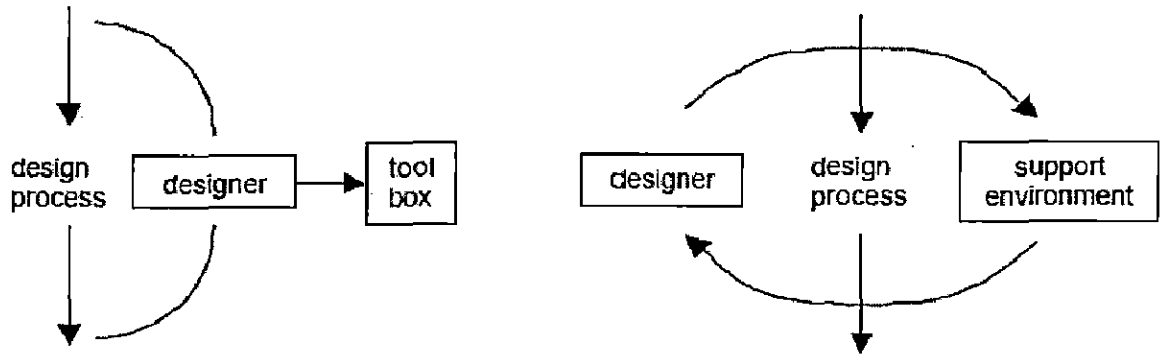
Figure 5.5 - One zone of a simulation model (including vertices)

Table 5.1 - Different components in a simulation program

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.
HVAC 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.

5.2.3 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. It has been described the difference diagrammatically as shown in Figure 5.6 and is referred as de-coupled and integrated simulation application. Efforts to enhance the general application of simulation should also encourage its integrated application.



(a) (b)

Figure 5.6 - Simulation (a) de-coupled from the design process and (b) as an integrated application

5.3 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.

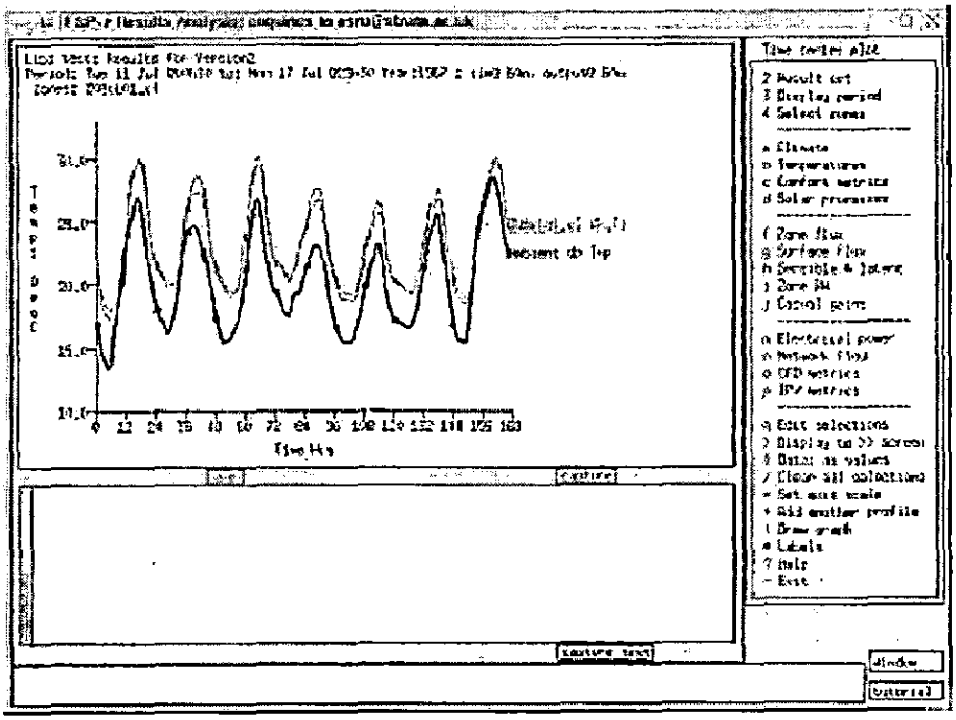
5.3.1 Performance prediction domains

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: refl-opt4_1.res: Results for refl-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	8.80	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	14.68	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	10.61	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 5.7 - Different output types: (a) tabular (b) graphical

5.3.2 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. Digital output is very cumbersome to investigate and is normally not applied in the analysis process. Tabular and graphical displays find wider application. Figure 5.7 gives an example for each type.

Figure 5.8 shows that performance communication methods can be further differentiated 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 behavior. Additional research is also carried out within the building simulation community into more innovative concepts of graphical display.

5.3.3 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).

5.3.4 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.

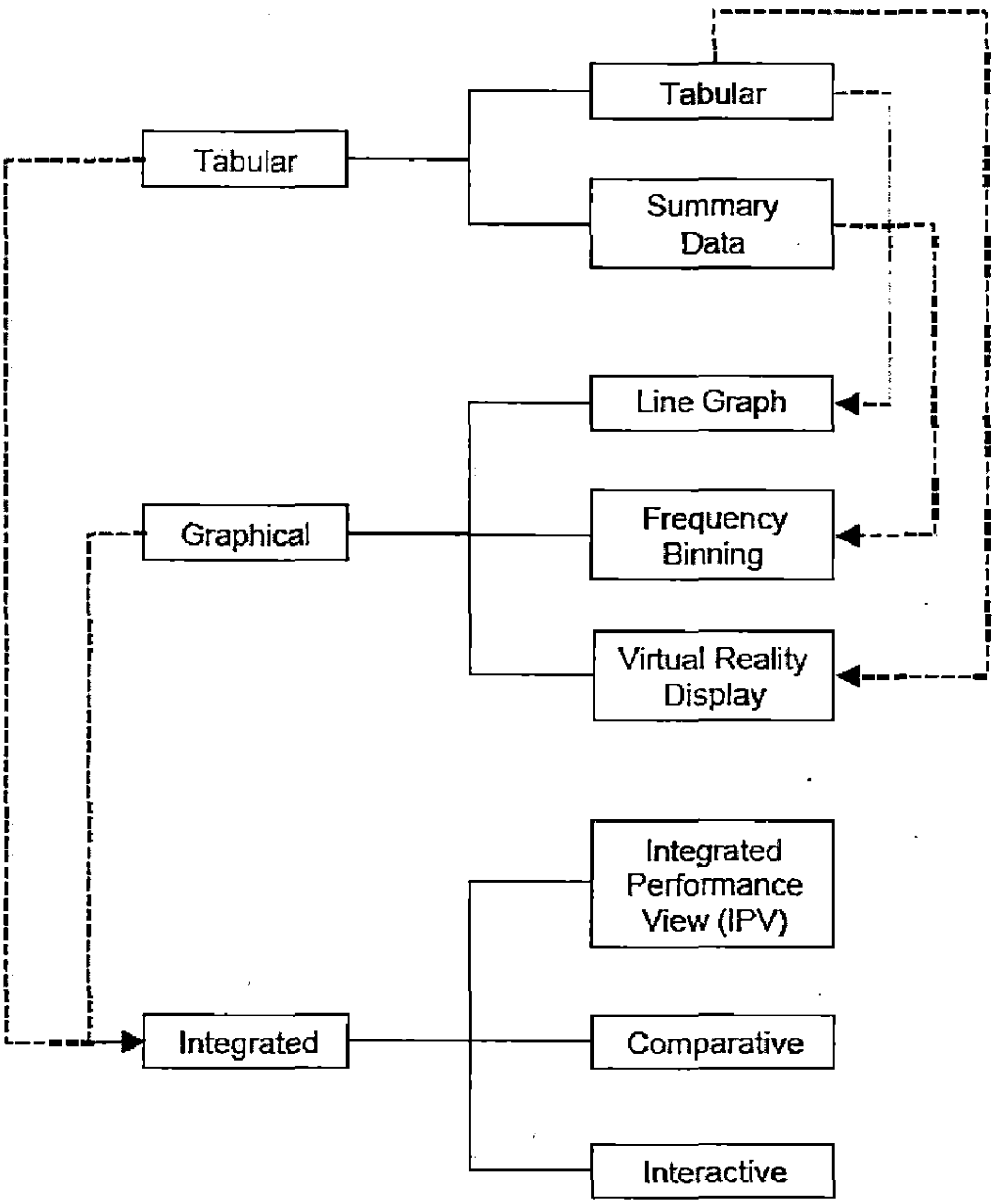


Figure 5.8 - Different performance communication methods

5.3.5 Graphical analysis

Although it is possible to analyze time series data in tabular form this often gives only limited insight into the behavior 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 analyzed.

Graphical display can vary from line graphs and bar charts to pie, scatter or radar charts. The main display types found in contemporary building simulation tools are line graphs and frequency binning, the latter mainly displaying summary data.

5.3.6 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 has developed Integrated Performance Views (IPVs), which are created automatically by the ESP-r simulation software.

Figure 5.9 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.

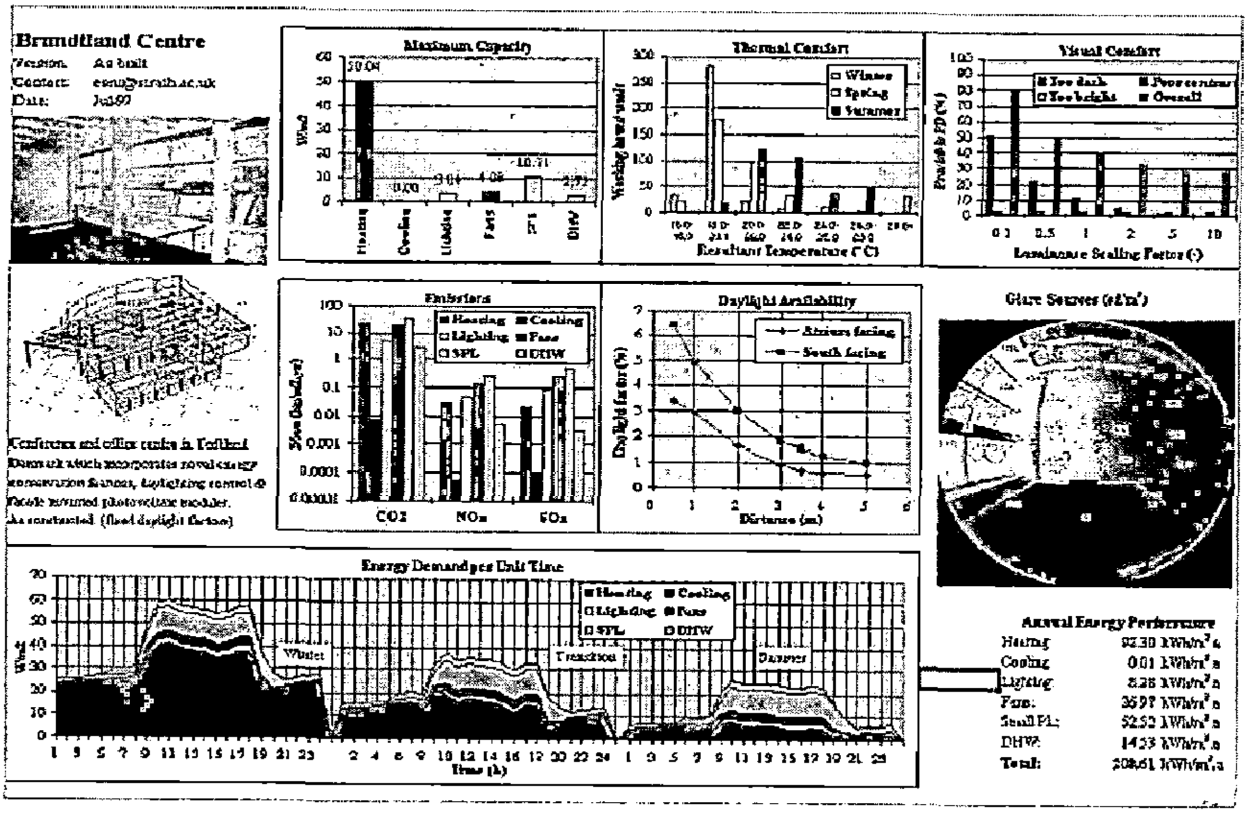


Figure 5.9 - An Integrated Performance View (IPV)

The development of IPVs has enhanced performance communication to the viewer. Their quick and easy generation and standardized 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 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 5.10 show the BDA Decision Desktop, displaying the performance of different models.

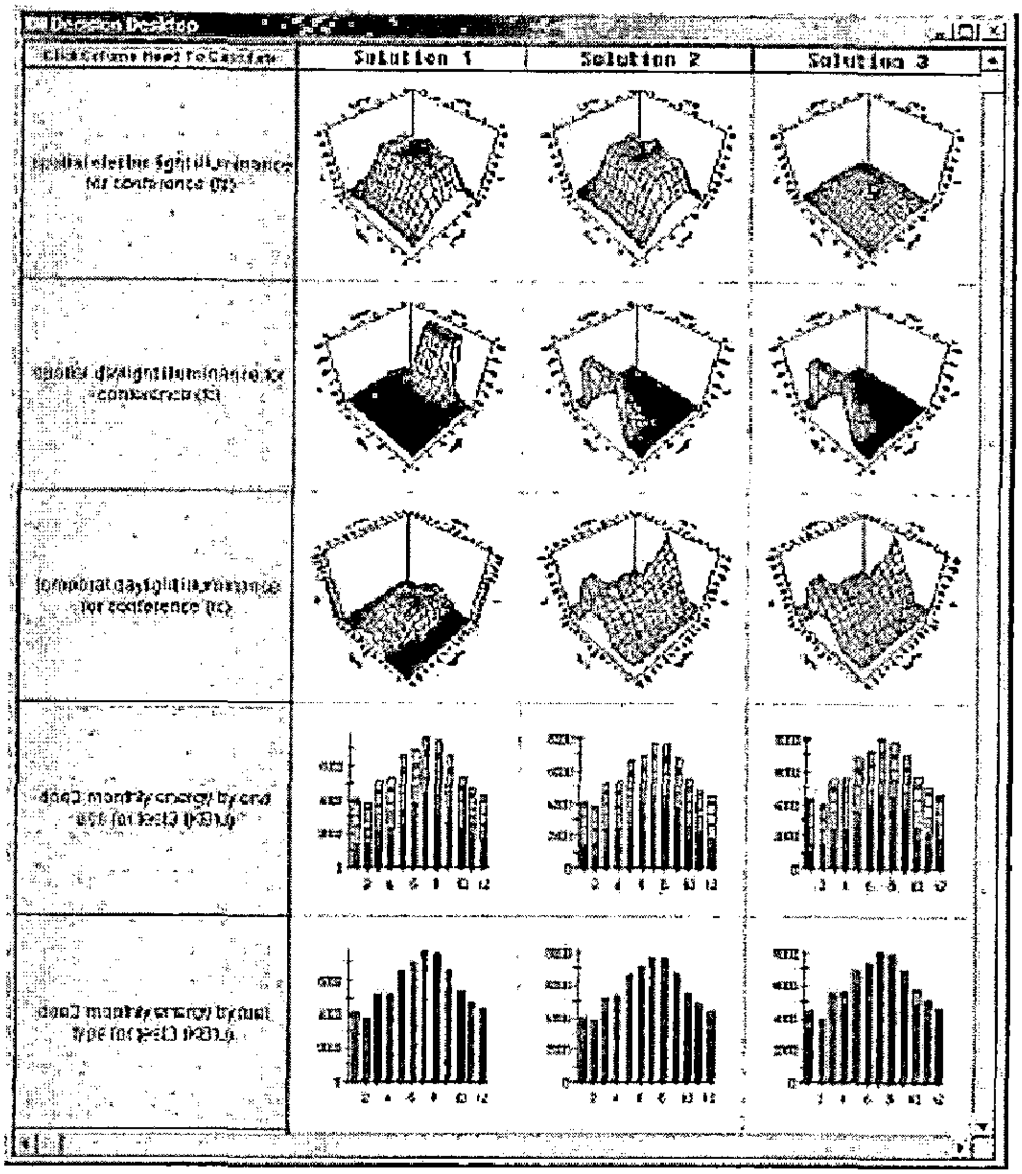


Figure 5.10 - The BDA Decision Desktop

5.4 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.

5.4.1 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. The differences are illustrated in the approaches by categorizing 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 5.11).

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 5.11 - Categorization of simulation programs (1-4 simple, 8-10 detailed, and 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 dynamic thermal simulation software it has been expanded over the last two decades to a simulation package with several additional simulation capabilities.

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 optimization 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 utilizes 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 visualization tools. While BDA is still under development, so far two simulation tools have been integrated into the software: an energy estimation tool and a day lighting tool. The aim is to include additional features such as air flow modeling and cost analysis, and to replace the current integrated simulation tools with more advanced simulation engines.

5.4.2 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; some of which evaluated specific simulation programs, others evaluated in general the capabilities and functionality simulation programs currently provide.

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.

Table 5.2 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).

Table 5.2 - Rating of different simulation program functions

	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	-	+	-	+

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. 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 research publications. Of the above listed simulation programs only the LT-Method is reasonably easy to operate for a non-frequent user. 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.

BDA and Energy 10 are more difficult in their operation. It is indicated that it is currently complicated to specify 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 it is suggested 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. 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.

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 L-T 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 set points 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 Auto Build 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. 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 is a limitation.

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 behavior. Another issue is to what extent a program produces information about energy flows in the building.

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.

5.4.3 Comparative discussion

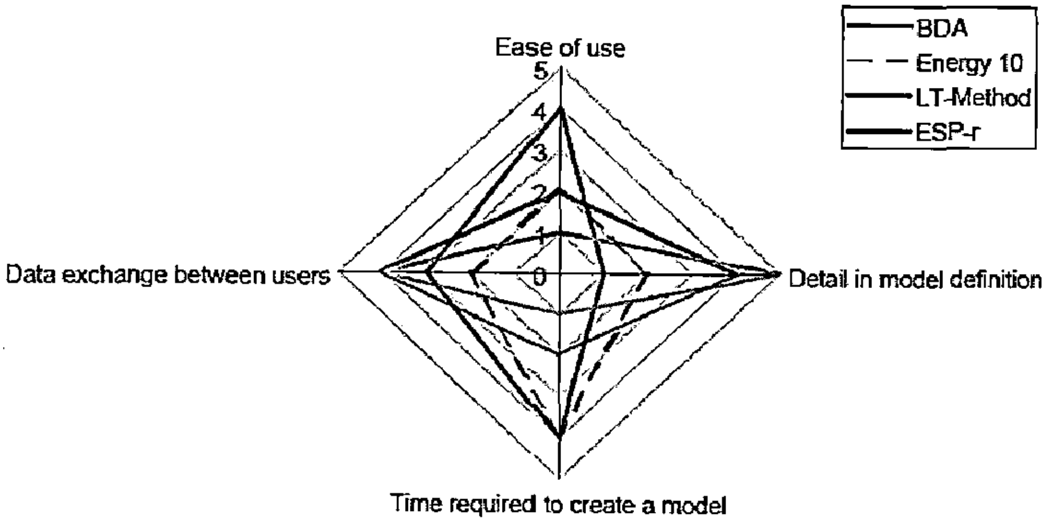


Figure 5.12 - Radar graph of the ratings of the different simulation programs (In the graph a high rating of ++ is equivalent to 5, a poor rating of -- equates to 1)

Figure 5.12 shows a radar graph that illustrates the ranking of the various programs with respect to their user functions based on table 5.2. 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 modeling detail the user can specify.
- The figure 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.

Table 5.3 displays from Table 5.2 the rating of the performance predictions that the different simulation programs provide.

- 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.

Table 5.3 - Performance predictions provided by the different simulation programs

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

5.5 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 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.

5.5.1 Relative unimportance of energy efficiency

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.

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, 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.

5.5.2 No structure for inclusion of simulation in the design process

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). 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 utilize building simulation at different building design stages.

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 utilized 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. 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.

5.5.3 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. This cannot be assumed for users who will typically use the tool at different building design stages. 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. This is an issue also of relevance for the application of dynamic building simulation in the building design process. 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.

It is distinguished 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.

Feature	Simulator	Simulation Language
Modelling flexibility	□□ ━━━	━━━▶
Duration of model build	□□ ━━━	━━━▶
Ease of use	◀━━━	━━━ □□
Time to obtain modelling skills	□□ ━━━	━━━▶

Figure 5.13 - Comparison between simulators and simulation languages

(Lower □□━━━▶ *Higher)*

5.5.4 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.

In addition, the advanced simulation programs currently available often do not give sufficient support to the user in carrying such an investigation. 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.

5.5.5 Uncertainty

Uncertainty of input data is an important aspect of building performance predictions. 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 behavior and systems control. The routine consideration of uncertainty by simulation programs would allow the analysis of a building in a more holistic way.

5.5.6 Validation

Validation has been an issue since the introduction of the first simulation programs. 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, 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 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 emphasized that inaccurate performance predictions can also be caused by incorrect model specifications by program users.

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 emphasized 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.

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.

CHAPTER 6

SIMULATION SUPPORTED INTEGRATED DESIGN PROCESS

Dynamic building simulation 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 utilization 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. 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.

6.1 THE DESIGN STAGES

The structure of the SSDP was based on the Design Plan of Work, which divides the design process into different stages. The 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 6.1. Three design stages were identified where simulation can make a contribution to an improved building design.

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

Table 6.1 - The design stages

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.

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 analyzed 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 coordinating 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, 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.

6.2 THE POTENTIAL ROLE OF SIMULATION DURING THE DESIGN PROCESS

This section discusses how simulation can support the design decision making at the Outline, Scheme and Detailed Design Stage.

6.2.1 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 finalized 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 realizing 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 a particular geometry (see Figure 6.1).

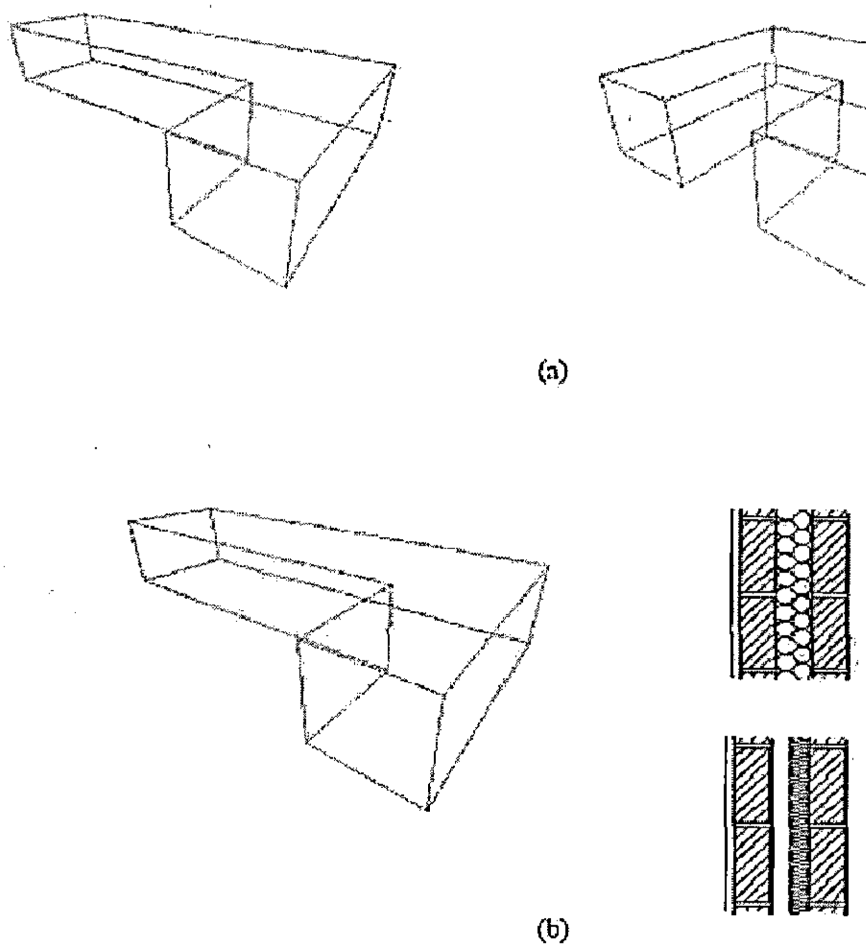


Figure 6.1 - Different analyses at the Outline Design Stage: (a) assessment of different geometries (b) analysis of the same geometry by changing the façade construction

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.

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

6.2.3 Detailed Design Stage

During the Detailed Design Stage, the building design is progressed in detail. By finalizing 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. At the Detailed Design Stage simulation also finds the widest application in the building design process.

In this context it should also be emphasized 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.

6.3 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 6.2. 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.

6.3.1 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.

6.3.2 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.

6.3.3 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.

6.3.4 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:

- The simulation engine of the simulation program, which performs the calculations.
- 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.

6.4 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 6.2. 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 customized to the different design stages. The ESP-r simulation engine 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.

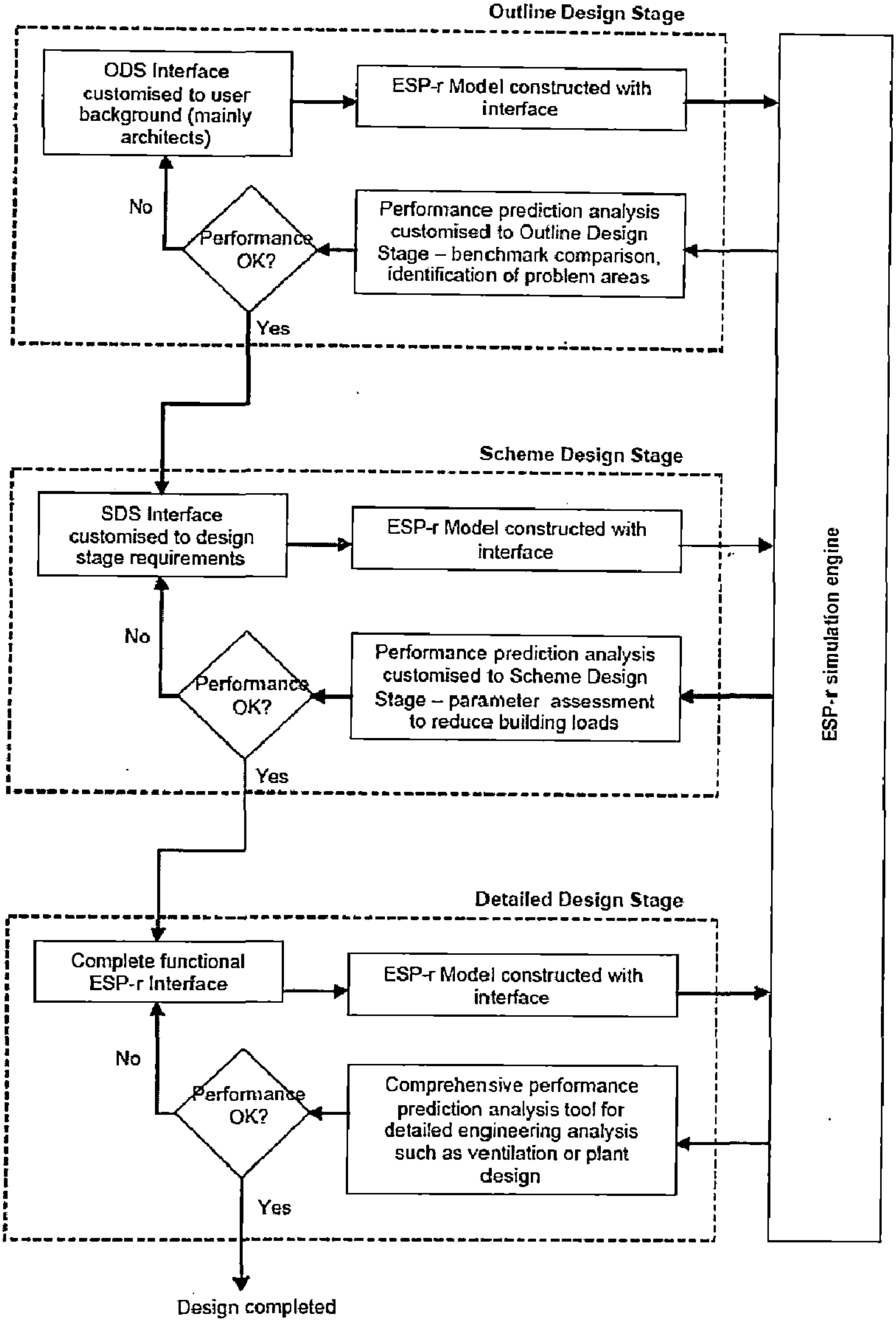


Figure 6.2 - SSDP implementation concept

6.5 DESIGN PARAMETER EVALUATION AT DIFFERENT BUILDING DESIGN STAGES

Figure 6.3 displays the different parameters identified as relevant for an evaluation with simulation tools at the different building design stages.

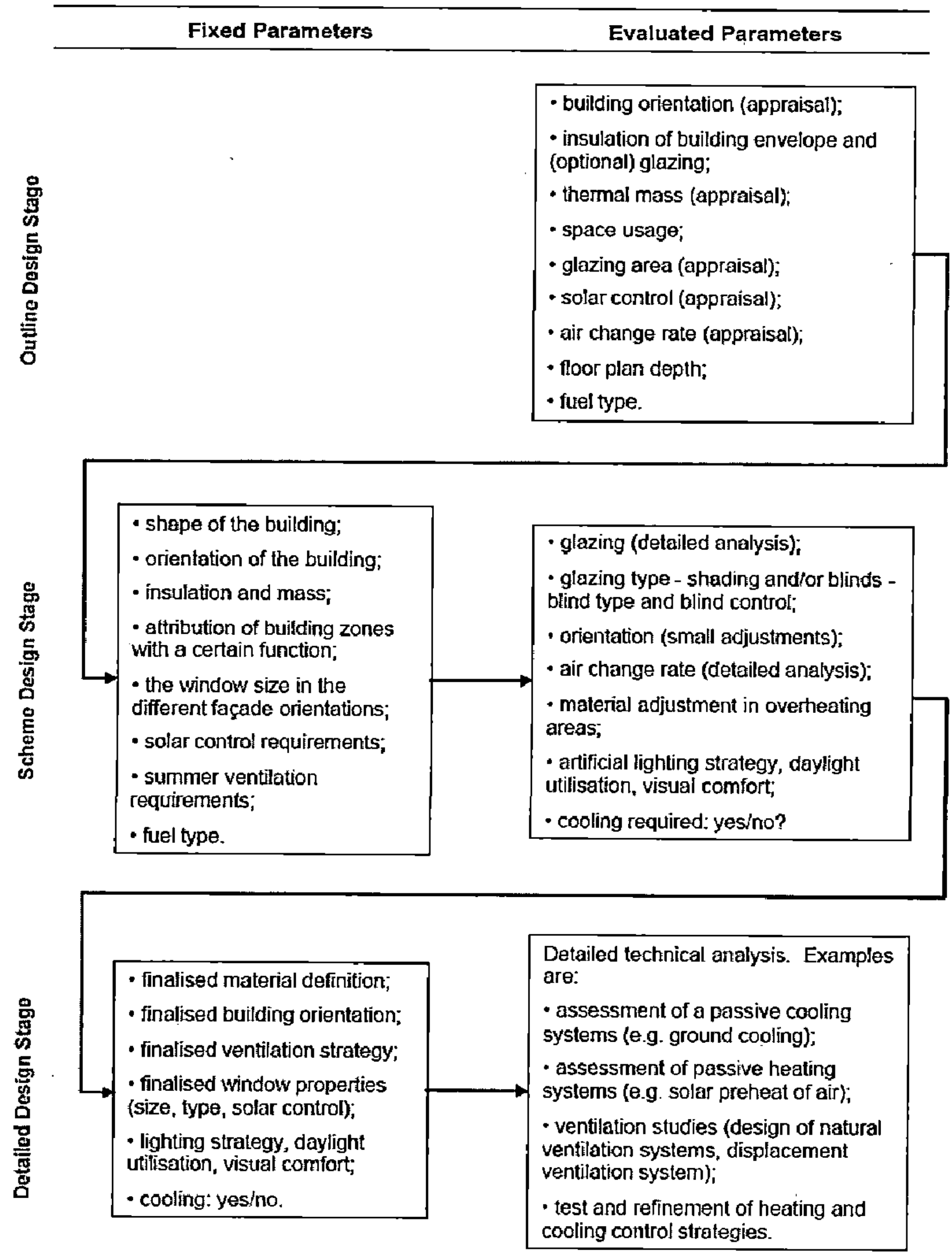


Figure 6.3 - Design parameters to be evaluated at the various building design stages

6.5.1 Parameters included in the Outline Design Stage

Table 6.2 lists design parameters that were identified as relevant for an evaluation at this design stage.

Table 6.2 - Design parameters evaluated at the Outline Design Stage

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.

6.5.2 Parameters included in the Scheme Design Stage

Table 6.3 lists design parameters that were identified as relevant for an evaluation at this design stage

Table 6.3 - Design parameters evaluated at the Scheme Design Stage

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.

6.5.3 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.*

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

An integrated approach to design buildings is important from both an economic and environmental point of view. The technology exists for substantial energy savings in the building sector but the potential for such savings has still to be fully exploited. To achieve efficiency goals, building designers require effective design tools for analyzing and understanding the complex behavior of building energy use. In the past decade, computer simulation and modeling has been used for providing an accurate and detailed appraisal of building energy design. Building energy simulation is a powerful, analytical method for building energy research and evaluation of architectural design.

However, the application of simulation in building design is problematic because the simulation tools are complicated and many building designers are not familiar with their properties and limitations. In real-life, the nature of the building design process and the shortcomings of current simulation tools have made it difficult for the architect to use such tools efficiently. There is a need to develop a better understanding of energy simulation and to put into practice the techniques for achieving energy efficient buildings. It is hoped that the information in this thesis can help increase an understanding of energy simulation techniques and encourage building designers to have the confidence to use the simulation based design tools.

7.1 BUILDING DESIGN AND SIMULATION ENVIRONMENT

Integration in the design of buildings is the result of how successful the designer has been in applying the technology and the energy analysis tools during the design process.

Design is feeling and thinking while acting. The building design process is characterized by one 'E' and three 'M': Evolutionary, Multi-criteria, Multi-discipline and Multi-solution. Inappropriate modeling of the design process may result in ineffective design tools and solutions. In general, there are two main categories of design:

- Architectural design that works on graphical images to determine the architectural form, shape, facade, etc.
- Engineering design that works on system schematics to perform thermal and HVAC calculations.

The following figure shows the relationship between design and simulation. The left hand side of the figure is the design context and the right hand side is the simulation context. There are interactions between the two that will facilitate transfer of data and knowledge for the purpose of design and performance evaluation.

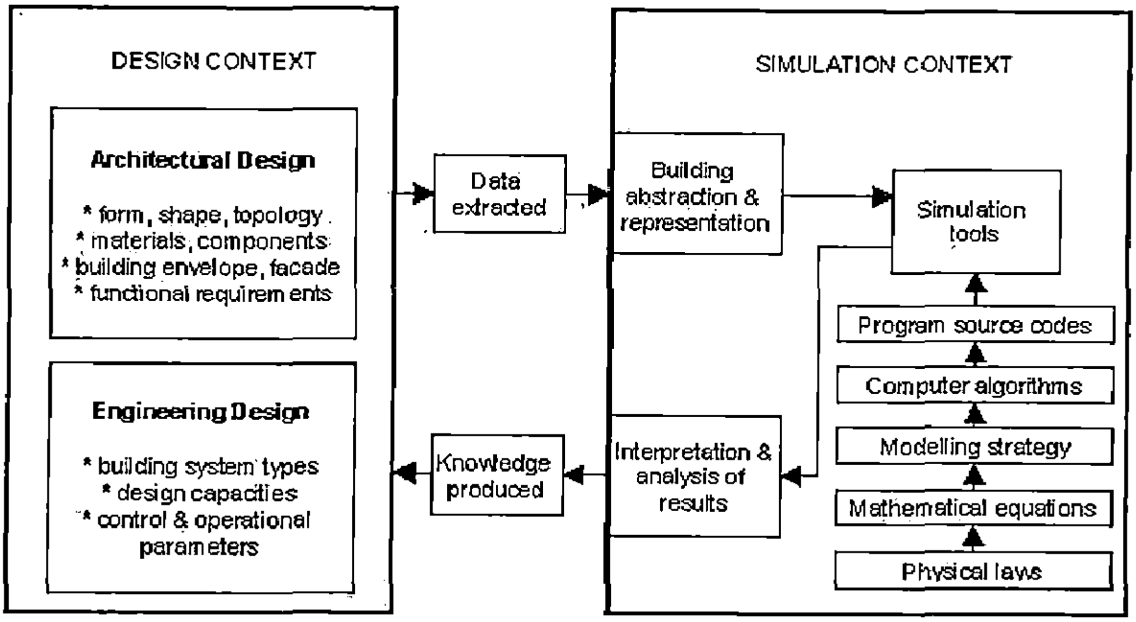


Figure 7.1 - Relationship between design and simulation

Architects usually develop their designs in drawing-based, graphical forms; prototypes are used to investigate the design concepts. What is important here is that building design is a creative process based on iteration: it consists of a continuous back-and-forth process as the designer selects from a universe of available components and controls options to synthesize the solution within given constraints. Figure 7.2 illustrates the evaluation cycle of architectural design.

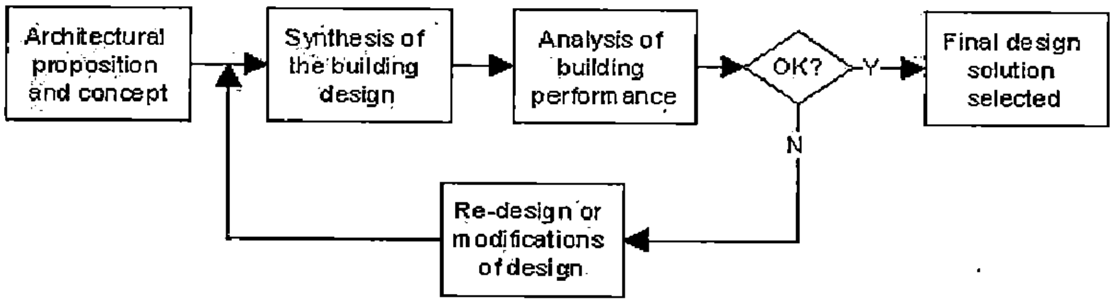


Figure 7.2 - Evaluation cycle of architectural design

A full range of architectural issues and criteria have to be considered simultaneously. The goal of design in architecture is to achieve the best balance of performances in a complete set of application criteria. Understanding the design and performance relationships is essential and this can be facilitated through simulation.

In real-life, however, building design often happens in a disorganized fashion and frequently jumps from concept to concept. Energy design is only one consideration amongst many and often not as important and prominent as the others. Since energy performance has usually been invisible, the most that could be hoped for in the past was that the architect would follow some general guidelines for energy efficiency and make sure the design fell within certain constraints. Since architectural design decisions have a significant impact on building energy performance, it is desirable to improve this area by an efficient simulation environment

7.2 EFFICIENT DESIGN PRACTICE

The following figure shows the possible applications of energy analysis at various stages of the building design process. At the early design stages, only conceptual sketches and schematics, often rough and incomplete, are available. As the design proceeds, more information and detail will be developed. If energy analysis starts early in the generative design phase, then energy considerations can be integrated into the building form and design concept. It is believed that the best opportunities for improving the energy performance of a building occur early in the design process.

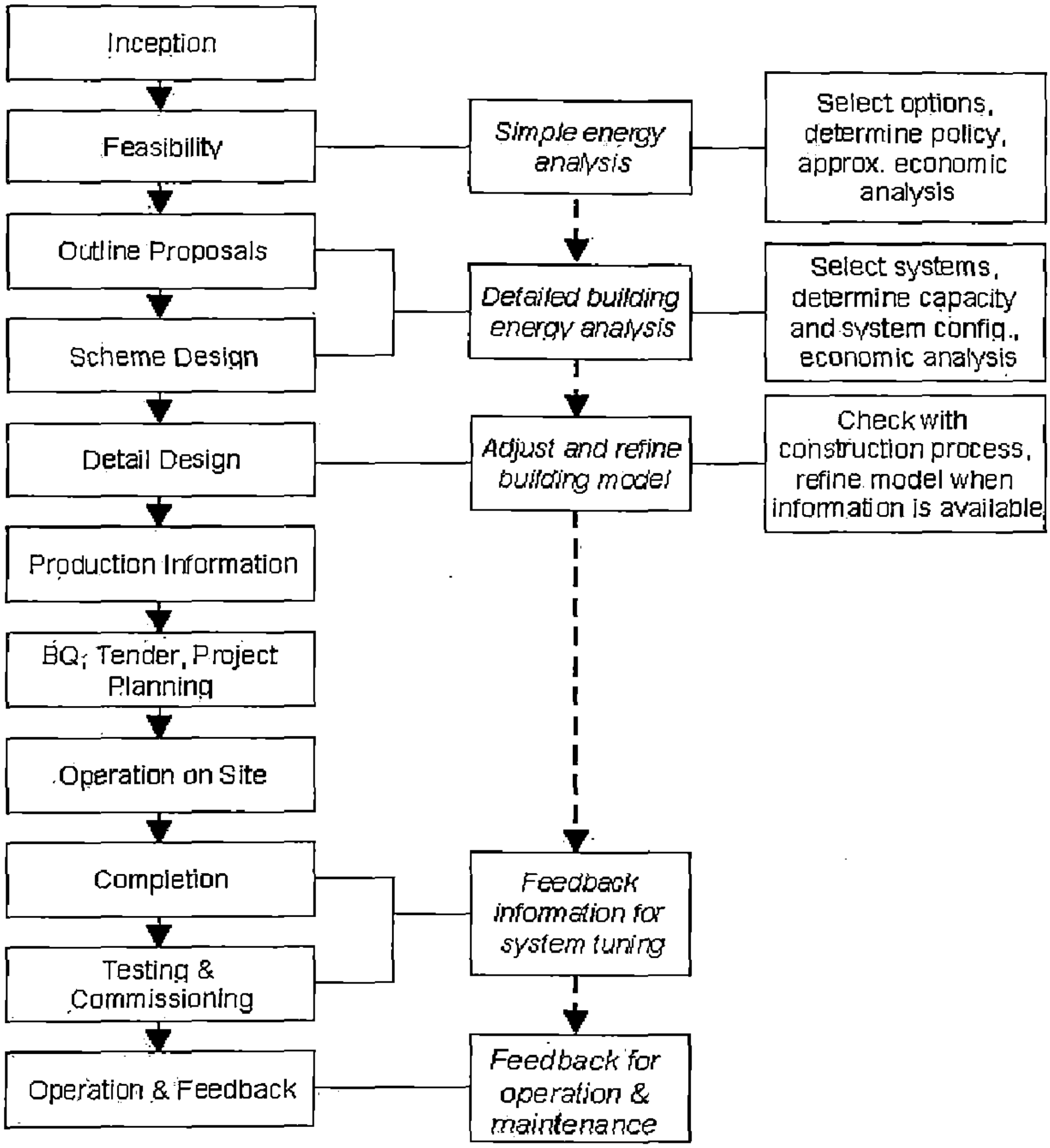


Figure 7.3 - The building design process

Because of the possible time and effort required for a full thermal analysis, detailed simulation tools are not efficient for all design exercises. Provisions of other design tools for a quick assessment of design strategies would be very useful. For instance, the use of solar path and shading facility can allow the architect to repeatedly evaluate a design concept on solar shading with a minimum amount of effort. Design tools with different levels of sophistication should be used to meet the needs at various design stages.

To solve a design problem using simulation, care should be taken to consider, *inter alia*, the nature of the problem and the approach of the investigation. Explicit knowledge on how to translate the problem into proper input and how to use the tool for evaluation is currently lacking. The seven major steps can be considered as a good framework for a successful analysis:

- Step 1 – defining the problem.
- Step 2 – specifying the model.
- Step 3 – data acquisition.
- Step 4 – implementation.
- Step 5 – planning.
- Step 6 – experimentation.
- Step 7 – analysis of results and reporting.

7.3 INTEGRATED BUILDING DESIGN SYSTEM

Integration of simulation into the building design process can ensure that important data and information for each major design decision is provided in a timely fashion. By establishing design links and exchange between architecture and engineering, an integrated building design system (IBDS) can be developed. Some researchers have taken the initiative to develop future IBDS for efficient and flexible use of simulation tools. The COMBINE (Computer Models for the Building Industry in Europe, http://erg.ucd.ie/combine.html) project in Europe and the AEDOT (Advanced Energy Design and Operation Technologies, http://apc.pnl.gov:2080/0projects_and_capabilities/aedot/html/aedot.html) project in USA are typical examples.

With the development of computer-aided design, building energy simulation and analysis is an important component in an integrated building design. Program development for future simulation tools consists of some of the following features:

- Fully integrated and interactive.

- Graphical user interface to streamline the data and knowledge transfer.
- Link with computer-aided design & drafting (CADD) tools.
- Data transfer between various building design software tools (then the design tools can be used in cooperative mode).
- Development of database and standard for building products.

7.4 CONCLUSIONS

As computer simulation tools are constantly changing and evolving, it is useful at this time to outline the current and future development of building energy simulation. Knowledge about the properties, applications and limitations of simulation tools is of practical importance because both current and potential users of the tools are, to some extent, frustrated and puzzled by the existing programs. To apply simulation tools and techniques successfully, a clear understanding of the building design process and its relationship with the simulation environment is advisable since humans (in other words architects) and not computers dictate the creative and evaluation process. For maximum efficiency, the integrated building design systems such as COMBINE and AEDOT currently being developed in other parts of the world will be an important step for the next generation of simulation tools.

The success of a design tool is only proven when many people in the building industry apply the tool successfully in practice. To evaluate building performance and achieve energy efficiency goals, architects and building designers should take full advantage of computer simulation tools that are readily available. With a better understanding of building energy simulation through education and training, it is possible for us to establish confidence and efficiency in the use of simulation based design tools.

7.5 RECOMMENDATIONS

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.

7.5.1 Test of simulation methodology in other design practices

The SSDP described in is based on research within one pattern of design practice. 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. 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.

7.5.2 Internet or Intranet based simulation software

The ESP-r software used as part of this research utilises a Data Base Management System (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 utilize simulation programs in the building design process. Internet and Intranet are becoming more used to connect offices located in different parts of the country. 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.

7.5.3 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 CAD software to specify simulation model designers can still not use the tool as pragmatic as they normally do but need to follow a number of conventions
- 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.

The designer gives much importance to the fact of being able to use a CAD tool for the specification of model geometry. Therefore research and developments should be carried out to remove the above stated limitations of the tool.

7.5.4 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. 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.

7.5.5 Uncertainty of input data

Uncertainty was identified as another barrier for the application of simulation within the building design process. Further research is however necessary to enable the routine application of uncertainly analysis as part of a simulation exercise.

7.5.6 Perspective

It is convincing that simulation will at some point be a routinely applied to address energy and environmental issues in the building design process (however, predictions of when it would occur varies 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, allowing a quick and easy model definition that will be generally applied in the building design process.

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.

- CIBSE (Chartered Institute of Building Services Engineering), "Energy efficiency in Buildings", CIBSE Publication, 1998.

- Eastman C., "The use of computers instead of drawings in building design", American Inst. of Architects.

- J. A. Clarke, "Building Performance Simulation Using the ESP-r System," presented at the fifth international IBPSA conference, Building simulation '97, Prague, Czech Republic, 1997.

- J.-B. Gay, J. H. d. Freitas, C. Ospelt, P. Rittmeyer, and O. Sindayigaya, "Towards a Sustainability Indicator for Buildings," presented at 2nd International Conference on Buildings and the Environment, CIB TG8, Paris, 1997.

- LBNL (Lawrence Berkley National Laboratory), "Building Design Adviser Homepage", http://kmp.lbl.gov/BDA

- Morbitzer C A, 2003, "Towards the Integration of Simulation into the Building Design Process", ESRU, University of Strathclyde.

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

- Robinson D, "Energy model usage in building design: A qualitative assessment", Building Services Engineering Research and Technology, Vol. 17, No. 2, CIBSE.

- Scottish Energy Systems Group (SESG) www.sesg.strath.ac.uk

- S. Citherlet, "Towards the holistic assessment of building performance based on an integrated simulation approach, Lausanne: Swiss Federal Institute of Technology Lausanne, Lausanne, 2001.

- US DOE (United States Department of Energy), "US DOE home page", www.usdoe.gov