CRANFIELD UNIVERSITY

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THE DEVELOPMENT OF A FRAMEWORK FOR INTER-DISCIPLINARY BUILDING DESIGN WORKING, AND THE APPLICATION OF INTELLIGENT KNOWLEDGE-BASED SYSTEM TECHNIQUES

SCHOOL OF MECHANICAL ENGINEERING

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Supervisor: Dr. W.J. Batty

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ABSTRACT

This work aims at establishing a framework for inter-disciplinary building design working, and developing a computer-based design aid which demonstrates the framework as well as enhancing the effective use of design information using intelligent knowledge-based system (IKBS) techniques. Design activities were initially discussed in logical terms taking account of stereotypes as starting points for design solutions. A conceptual model of design activities was then proposed, where these were characterised in terms of three different features, i.e. *information*, *design decision* and *performance*. Subsequently, the building design process was structured into a hierarchy of *design issues* and *design tasks*, and was then described rationally, relating to the conceptual model, in terms of three kinds of *design variables*, i.e. *information*, *design decision* and *performance variables*. The information regarding the design process was, meanwhile, elicited from publications with particular reference to daylighting and lighting design aspects, and itemised into a number of knowledge units. Based on this information, a framework for inter-disciplinary building design working was eventually developed, where design activities are considered in terms of the relationships between the *design variables*, and, as a result, a logical sequence of the design process was established. In order to clarify the parallel inter-disciplinary aspects of the building design process, the design knowledge was examined based upon the framework, and, eventually, developed into a checklist for inter-disciplinary building design working which has a process-checking capability. Subsequently, a prototype knowledge-based system was developed on the basis of the framework, using a commercially available expert system shell, *Leonardo*. Examples of stereotypes also formed a part of its knowledge. Demonstrating the checklist for inter-disciplinary design working, this prototype knowledge-based system proved the viability of the checklist approach, as well as showing its process checking capability. It also exhibited its potential ability to provide appropriate information at pertinent stages.

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ABBREVIATIONS

ADF	Average Daylight Factor
AI	Artificial Intelligence
BRE	Building Research Establishment
CAD	Computer-Aided Design
CIBSE	the Chartered Institution of Building Services Engineers
COMBINE	COMbined Building Models IN Europe
Da	*Design aspects*
Dd	*Design decision variables*
DTPs	Design Tool Prototypes:
EKS	Energy Kernel System
HCI	Human-Computer Interface
IBDS	Integrated Building Design System
ICAIS	Intelligent computer-aided instruction systems
IDM	Integrated Data Model
IFE	Intelligent Front End
IKBS	Intelligent Knowledge-Based Systems
In	*Information variables*
ISO	International Standards Organisation
ITS	Intelligent Tutoring Systems
M_{DdDd}	Design Decision-Design Decision Matrix
M_{DdPe}	Design Decision-Performance Matrix
M_{InPe}	Information-Performance Matrix
M_{InPc}	Information-Performance criteria Matrix
M_{InDd}	Information-Design decision Matrix
Pc	*Performance criteria*
Pe	*Performance variables*
RIBA	the Royal Institute of British Architects
STEP	STandard for Exchange of Product data
TAS	Thermal Analysis System

Chapter 1

Chapter 1

INTRODUCTION

1.1 Motivation

During the last 20 years, building technologies have seen rapid changes in terms of structural design, materials and management systems. Various kinds of building envelopes have been introduced into commercial markets and sophisticated building management systems allow a more delicate and complex environmental control. As a result the technical information handled in the building design process has increased considerably, and the standard of buildings which clients require, in terms of energy efficiency, amenity and comfort for the users, is becoming higher. This trend will continue, and may even escalate in the future. Since the clients are becoming increasingly sophisticated in their understanding of building performance and its associated running cost and social implications, greater demands will be made for quality-assured, safe, comfortable and flexible buildings which provide a healthy internal working environment and have a minimal impact on environmental pollution.

Buildings have, however, often suffered from low efficiency in accommodating the needs of their owners and occupants because of shortcomings in their design and the way in which they are operated [Batty 1990]. Most of the shortcomings can be attributed to the increasing complexity of buildings and building systems and the inefficiency of building design activities. In this sense, an understanding of the behaviours of buildings and new products, and the information related to them will play a more vital role within the design process than they have ever done before. The flexibility and efficiency of the design process also needs to be enhanced while maintaining the quality assurance of the building structure and systems.

Recent developments of computer technologies have brought a new perspective to the building design activities in terms of computer-based design aids, such as computer draughting methods (computer aided design, CAD) and various building simulation programs. Although a number of sophisticated simulation programs have been developed, they have often failed to improve the productivity of the design process as a whole. Because many of these programs are based only upon one or a few particular aspects of the building design they are too specific to manage every aspect of the building design efficiently.

In order to improve the productivity of the building design process as well as achieving a quality-assured building, it would be advantageous to develop an intelligent design aid which allows designers to access necessary information and also helps them to work in the context of the building design. Consequently, this study intends to provide perspectives for such an intelligent design aid. In this sense, the application of intelligent knowledge-based systems techniques could possibly provide measures to achieve such an aid. But, this kind of design aid may require the establishment of a framework for the design decision-making process to cope with the complexity of the building design. This study, therefore, involves a wide range of topics, such as:

- A study of the design process (how designers work);
- Energy and built environment;
- Information usage during architectural design; and
- The use of computer-based tools as design aids.

In the rest of this chapter, the background of this project is presented. In the next section the nature of design in general is considered, leading to the building design process in particular. After discussing the characteristics of the building design process, potential problems which may cause inefficiency of the process and consequently threaten the quality of the building are addressed. Then, the conceptual basis for the development of an intelligent design aid to overcome these problems is discussed in terms of inter-disciplinary design working, information transfer and an integrated design environment, by referring to current relevant literature related to them. Finally, the aim of this project is expressed and the programme for its achievement is explained.

1.2 Background

1.2.1 Nature of design

'Design' encompasses numerous disciplines: architecture, fine art and all types of engineering design. A number of definitions could be given from different views of design. In Waldron [1989], for example, 'design' is defined as:

- art rather than science;
- a mental plan of taking some ideas and transforming them into products which satisfy the specification; and
- the refinement of functional specifications to artefact.

It is not easy to give a comprehensive definition of 'design' that represents both the common and the disparate features of all these disciplines, but, it seems sensible to assume that 'design' has the following features. It is a **purposeful activity** which involves a conscious effort to arrive at a desired state which designers have in mind. In other words, 'design' appears to be a process of originating systems in order to attain a certain desired state, i.e. a goal. In this definition, a design is not the final artefact, but a description of the artefact from which the predictions of its eventual performance can be made. The design itself is, therefore, merely "an abstraction providing a description of an artefact that can be interpreted by some other agent for the purpose of manufacture or construction [Coyne et al., 1989, p.5]."

Design can also be seen as a **goal-directed activity**. It involves making decisions in order to produce a set of descriptions of an artefact that satisfies a set of performance requirements and constraints. The activity may begin with recognising dissatisfaction, and a state of satisfaction is defined as a goal or goals, and then objectives are set to achieve this state. The ability to set goals and plan for their attainment is a powerful and essential human capability.

The process of determining a goal is poorly understood, however. A goal may be dependent upon the designer's own particular system of values, which will differ from those of other individuals, both within and from culture to culture. Even given an agreed goal, different designers will interpret it from their individual point of view. As a result, they may set different objectives, and a number of different potential approaches to their achievement could be attempted. There is no straightforward process to follow, and there may even be no fixed starting point. In this sense, design can be an **ill-defined activity** that involves exploring partial solutions which eventually lead to the re-definition of goals.

1.2.2 What is a building?

Designing a building is a purposeful, goal-directed, and often ill-defined activity. It involves a wide range of inputs including art, various engineering disciplines, materials science, physics, physiology and even psychology. The setting goals and the conscious efforts required to attain them should always be accomplished in the context of human needs, i.e. shelter, and the physical and psychological quality of existence. Considering these needs in terms of the functions of buildings, several definitions of the artefact, i.e. a building, could be drawn.

At the most basic level, the primary human need related to a building is that for shelter which provides protection against the many agencies of the immediate environment including climate, natural disasters, wild animals and other humans. In this context a building is defined as a "*shelter*" for survival which produces safety and security within it.

As societies have developed and become more distant from the more extreme aspects of natural environments, the concept of *shelter* has then become more closely aligned with the modification of the effects of the climate. The development of the skill to build shelters together with clothing has extended the range of human survival to all the world's climatic regions. In extreme climates buildings have developed which largely exclude the ambient environment, for example, an igloo. In more temperate climates, however, an obvious connection often exists between the internal and the ambient environment. Solar energy, for instance, may be used to 'improve' the internal environment both with regard to temperature and light. In such circumstances, it becomes clear that once survival conditions are attained building occupants extend their requirement to the secondary human need to provide comfort within the shelter, i.e. concern for the physical quality of existence. In this sense, a building can be seen as a "*climate modifier*" which magnifies or depresses the effects of particular climatic aspects to fulfil the conditions of better physical quality.

As buildings became more than mere shelters a distribution of activities occurred within them. Thus functional differentiation of space developed. As a result of such functional developments, buildings eventually became differentiated in the same way into domestic, administrative or religious building, or storage etc.. In this context a building can be said to be a "*space constrainer*", or accommodation, which encloses a space for a particular and well-defined function.

When both the human needs for shelter and the physical quality of existence, are fulfilled, the building owner will become aware of and wish to consider an additional human need, i.e. the psychological quality of existence, expressed as a sense of aesthetics. A building may often please the aesthetic perceptions of viewers, as, for example, a land mark in harmony with its surroundings. Furthermore, it is significant in terms of sociological and environmental senses that a building may make a statement about the owner's or business's status and self-esteem. In this context a building can be defined as an "*aesthetic definer*".

In order to construct a building, land is needed on which it can be erected. Constructing the building involves development of the land, and the building can add further utility and value to the land once it is completed. A building can therefore be defined as a "*land modifier*". Moreover a building requires resources, i.e. materials and energy. In other words, building elements such as bricks are manufactured from raw materials and transported to the site where the building is being constructed. Also energy is used during the construction and operation of the building as well as during the manufacturing and transporting the building elements. In this sense a building can be said to be a "*resource modifier*" and be considered as the culmination of the management and utilisation of raw materials as well as the embodiment of energy.

1.2.3 Building design process and its characteristics

Building design procedures in Britain have hardly changed for many years. The case studies carried out by Mackinder and Marvin revealed that the work in architectural offices tends to follow a consistent pattern [Mackinder and Marvin 1982]:

> "an initial concept for the building plan, form and general construction of a new building is developed rapidly using little information other than the client's requirements, site constraints and the designer's own experience. This initial concept is then developed and refined using more deliberately researched information, and later modified as necessary in response to emerging constraints and changing requirements."

This pattern may follow the basic process outline as described by the Royal Institute of British Architects, RIBA, *Plan of Work.* According to the RIBA *Plan of Work*, the work involved in building design and construction falls into the following broad sections [RIBA *Architect's Job Book: Volume 1 Job Administration*, 1988, p.15], namely:

- Inception
- Design and production information
- Contract procurement, and
- Project planning and site operations.

The RIBA *Plan of Work* subdivides these operations into a programme of 12 stages. As shown in Figure 1.1, the '*inception*' section can be subdivided into two stages: '*inception*' and '*feasibility*'; and the '*design and production information*' section can be further divided into four stages, i.e. '*outline proposals*', '*sketch design*', '*detailed design*' and '*production information*'. In this thesis, the building design process is considered to comprise these 6 work stages in terms of the RIBA *Plan of Work.* Here, the earlier part of the design process, which consists of the first four stages, has been defined as the '*strategic phase*', and a rest of it, i.e. *detail design* and *production information*, the '*tactical phase*'.

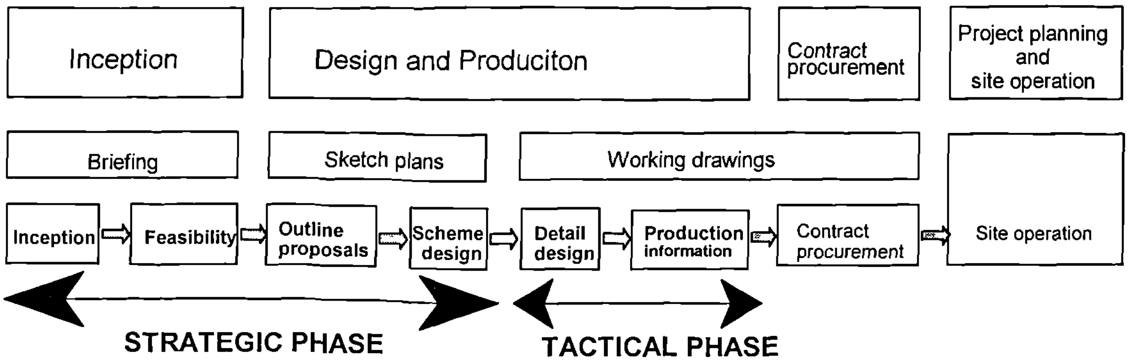


Figure 1.1 Outline of the Royal Institute of British Architects, RIBA, *Plan of Work*

Designing a building has the following characteristics, namely:

(a) a multi-disciplinary activity, and

(b) a time-constrained activity.

Considering the definitions of a building as described in the preceding subsection, it is understood that designing a building has aesthetic, economic, functional, and technological implications. McDonald described building design (architecture) as follows [McDonald, 1980]:

> "Architecture is a complex undertaking involving technical, social, utilitarian and cultural problems. In short, it is the systematic arrangement of knowledge, it involves the making of beautiful forms, ordering space in a coherent manner, use of materials in a functional and knowledgeable way and providing comfort and convenience for its clients and their activities."

Because of these diverse features of a building, designing it requires the active participation of different professions as well as a client. The process of the building design, therefore, needs to be undertaken by a design team comprising several professionals from different disciplines, such as an architect, quantity surveyor and engineers from various backgrounds (Figure 1.2). Considering the multi-disciplinary nature of building design, many design problems need to be addressed and solved by the members of the design team, in parallel, and separately, whilst still considering other aspects of building function. This implies that timely communication should occur between these members during the course of design to make sure that every aspect of the design meets the requirements of the brief. It is, therefore, understood that communication between these members is crucial for consistent development of the building design. An inter-disciplinary working methodology should be one of the essential characteristics of building design, particularly as modern buildings have been becoming more complex in terms of the requirements and the choice of systems to achieve them.

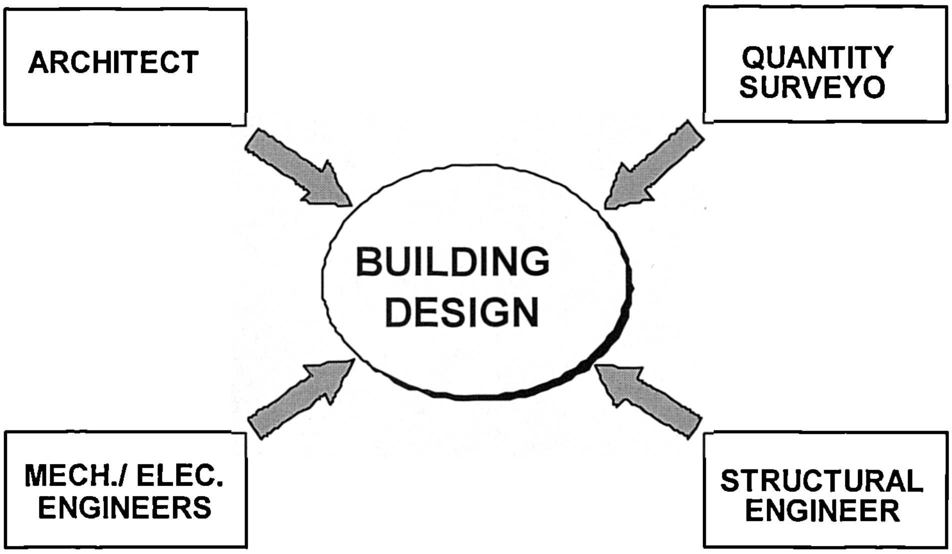


Figure 1.2 Building design: a multi-disciplinary activity

The building design process has another distinctive characteristic: it is a time-constrained activity. Figure 1.3 shows the distribution of design decisions throughout each of the design stages. The percentage of design time that architects spend, on average, on each of the design stages, is described by the height of the columns. The diagram indicates that over 40% of the total decisions are made during the sketch plan phase, whereas only 19% of the total time is allotted to this activity.

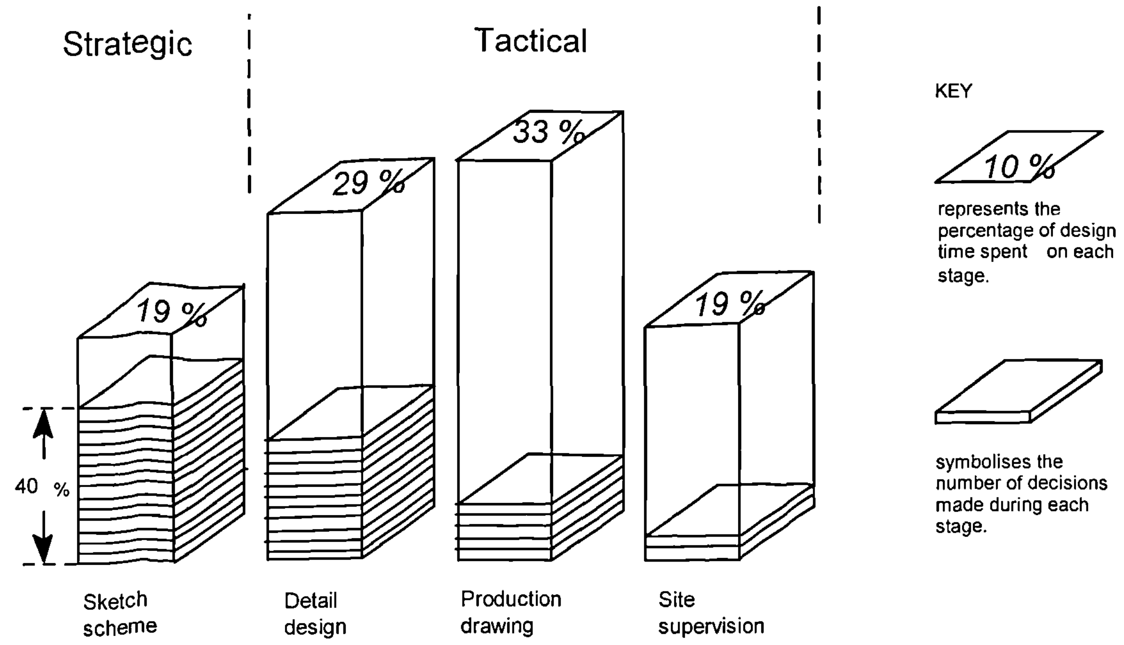


Figure 1.3 Distribution of decisions in each design stage [RIBA, "Employment and Earning Survey", 1984]

The case studies observed by Mackinder and Marvin [1982], importantly, found that the initial concept developed during the inception phase of the building design process tended to form the general basis of the final design, only undergoing minor changes. This could mean that decisions made during this very early stage strongly affect the following tactical design activities and the final behaviour of the completed building. But, the diagram in Figure 1.3 implies that the greatest risk of making a design mistake exists in the early design stages, where designers tends to rely heavily upon their previous experience because of the pressure of time. A single optimal solution which completely satisfies both the client's requirements and legal regulations rarely exists, although there are many alternatives to choose from during the building design. Once the '*scheme design*' stage is completed (see Figure 1.1), ideally the brief should not be modified, because this will cause much of the previous work to be aborted [RIBA, 1988]. The designers, therefore, ought to consider a wide range of options at the start of the design process and follow these through to the completion of the sketch plan phase. In order to improve the productivity of the design process as well as assuring the quality of the realised building, it is vital to examine alternative designs and also to use the full range of information available, including experience gained from previous projects.

1.2.4 Problems of the building design process

The research reported in the previous section leads to the conclusion that the following problems often occur, causing inefficiency of the design activity and potentially the danger of building failure.

(1) An inherent problem of poor communication

The fact that designing a building involves professionals from various disciplines often involves an inherent problem of poor communication between them. The deeper the involvement of each professional in their field, the more difficult communication with each other becomes, in terms of their languages (vocabulary), willingness and interests [Building Services, 1985]. Often an unwillingness to consider others' points of view may even exist between members of the design team, because the professionals want to be 'experts' within their own disciplines and do not always welcome interaction with other professions. The manner in which fees are allotted to different aspects of the design work often helps to foster this attitude.

As a result, since design problems are usually tackled by the individual professionals from their own points of view, one member's design decision may become another's problem if a design feature related specifically to one of the disciplines is resolved in isolation. In order to solve any conflict that may occur, feedback to the '*analysis*' phase will be required and the '*analysis-synthesis-evaluation*' process will be reiterated. Although this is an inherent and often positive aspect of the design process, the productivity of the design activity is reduced if such feed-back occurs too frequently due to inadequate decision-making structures with poor communication.

(2) Isolation of team members

The problems arising from an inadequate communication structure do not only relate to the frequency of feedback within the process, but also to the fact that some team members are not involved in the design process until the later stages when many of the decisions that may affect their work have already been made.

There is a risk that if conflicting design decisions have been made, such a problem may not be recognised or discovered until the design is well developed. It will then be necessary to back-track to a previous design stage so that origin of the problem can be reconsidered, otherwise the design process is carried forward through a compromise solution with the acceptance that a more appropriate solution could have been employed. Such back-tracking is likely to result in abortive work and to affect the productivity. In an even worse case, if the problem remains undiscovered, it will cause poor performance of the building, and will, consequently, threaten its quality-assurance.

(3) A linear chain of communication within the traditional design team arrangement

The problem of poor communication can partly be related to the traditional structure adopted by the design team. A typical design project arrangement is shown in Figure 1.4. This arrangement has a hierarchical structure. A client requiring a building may usually consult an architect. The process of design begins, inspirations occur, and plans to bring them into practice are harnessed by the architect. An inherent risk in this arrangement is that only the architect acting as a team leader enjoys a close relationship with the client. The position of the quantity surveyor may be enforced by his understanding of the financial aspects associated with the project, and, as a result, he sometimes has a closer relationship with the client than the architect. To the engineers and the other members of the design team, it often seems that the communication route is only one way, from the architect and the quantity surveyor downwards, instead of being a two-way process. In this arrangement, there is a danger that some members of the design team are not involved in the process until a later stage when a brief has been formed. As buildings and the systems within them are becoming more complex, such a linear chain of communication, or 'top-down' approach, is likely to result in an inefficient design process where the feedback loop from '*evaluation*' to '*analysis*' occurs excessively frequently.

Another shortcoming of this arrangement is that the client can rarely meet any of the design team members other than the design team leader, the architect for instance. Is it not better for a client to meet a building design team, i.e. architect, quantity surveyor, structural engineer and services engineer, together from the outset? This forms the basis of collective decision making, ensuring that a complete brief and specification with suitable budget allocations for structure and services is prepared [Croome, 1983].

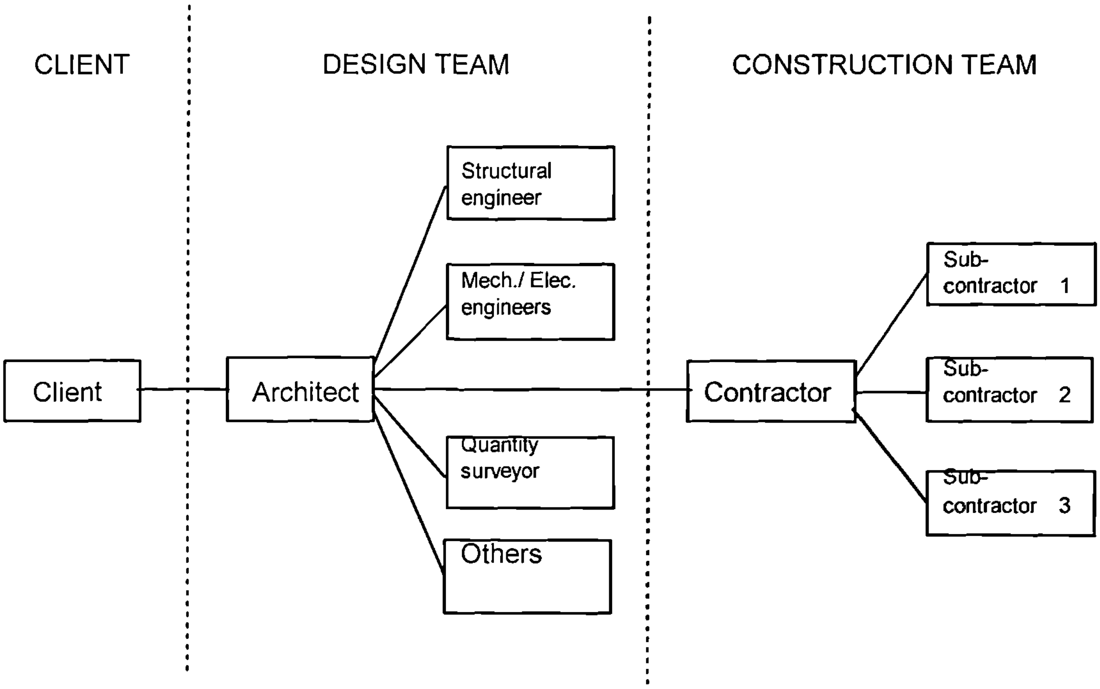


Figure 1.4 Typical project team arrangement [King, 1989]

(4) Too discipline-specific computer tools

Nowadays a number of computer programs for building design are available, and some of them are highly sophisticated. To enhance the productivity of the building design process and quality-assurance of the building, it should be vital to make use of the power of these software packages as well as establishing a good communication structure within the design team.

The existing software packages such as CAD (computer aided design) and sophisticated simulation programs are, however, generally discipline-specific, and support only a part of the design process, such as cost, structure and thermal aspect, individually without any concern for the broader implications of their predictions in the design context. As a result, these tools tend to reduce, rather than enhance, the opportunities for communication between the design team members.

In addition, since the aspect-oriented feature of the design tools requires a specific data structure for each of them, the likelihood of inconsistency between the design aspects of these tools could exist. It may be a struggle for the designers to keep any consistency within their design aids whenever a design is modified. Consequently, the lack of integration in the design context could diminish the opportunity to explore design alternatives during the course of the '*analysis-synthesis-evaluation*' cycles, and even reduce the productivity of the design process.

(5) Temptation to skip the evaluation activities

The case studies carried out by Mackinder and Marvin [Mackinder and Marvin 1982] also found that very little exploration of alternatives took place during the early, 'strategic', phase of the process, because of the time pressure. Ideally, to ensure a quality assured building design, a number of alternative designs or design strategies should be examined from various points of view within the strategic phase of the design process, where the initial concept of the building design is formed. In reality, however, because of the time constraints, exploration of alternative concepts is rarely allowed. Once an initial concept is established, it is developed considering only a few alternatives related to that particular concept. The temptation to skip the evaluation activities may even exist in these circumstances. This could have serious consequences if new materials or systems are used for the first time. As a result, design decisions may be based on inadequate or poorly researched information, which may cause severe disruption to the project if discovered at a later stage.

(6) Inadequate use of information

Pressure of time may also lead designers to rely on their experience and well-tried concepts, rather than taking risks with new materials or systems. Marvin revealed the fact that, because of time pressure, designers tend to rely largely on solutions used previously without known mishap, and did not always recognise the need to look for more up-to-date information or to consider alternative solutions [Marvin 1985a, 1985b]. This attitude of the designers, together with the temptation to skip the evaluation activities, introduces the risk that they could apply old solutions inadequately to new circumstances. When regulations change, for instance, their full implications are rarely understood until several years after their implementation, and this often only occurs after poor performance or failure are noted in recent buildings. This information then becomes part of the new experience set. However, the sensible use of design tools usually can predict that these problems are likely to occur if designers use "out-dated" rules of thumbs.

Furthermore, extensive information is required nowadays. As explained in Appendix A, Mackinder and Marvin [1982] found that experienced architects in the architectural offices produced the outline of their designs and then the less-experienced staff are required to make the detailed decisions while carrying out their evaluation in order to implement their seniors' plans. When these less-experienced designers are dealing with detailed technical aspects, they appear to refer to written forms of information frequently as well as seeking necessary information by asking questions to their knowledgeable colleagues. As a result of the technological development, however, there are a number of possible information sources to consult, which range from the legislation documents to product information published by manufactures. Meanwhile little time is available for thoroughly searching through this information. In order to enhance adequate use of information, it is necessary to provide 'more extensive information', which includes the senior members' expertise as well as written form, so that the designers could access adequate information at an appropriate time.

(7) Problems of information transfer

Mackinder and Marvin's case studies [Mackinder and Marvin, 1982] suggest that experience does help the designers to work more efficiently. Since the routes dictated by design decision-making are thought to strongly reflect the experience, especially that of design process, of the designer, these design routes recorded in connection with projects could be a good information source in terms of the timing of particular decisions within the process. Such recorded information would help to ensure adequate use of previous experience and relevant design information. Consequently, improved productivity of the design process as well as a greater confidence in the assured quality of the design would occur, if information, such as the sequence of design decisions together with the circumstances in which these decisions were made, could be referred to at the moments of decision-making during a later design process. It could also help less-experienced designers to work more efficiently and learn good habits.

However, the reality is that comprehensive records are rarely kept by architectural offices because of the pressure of time [Mackinder and Marvin, 1982]. An individual may gain the experience while working with the practice, but the design knowledge becomes only 'his', rather than belonging to the practice. If this individual leaves the office then his experience goes with him and a valuable knowledge and information resource has been lost. As a result, the offices may in the future lose some part of their design knowledge, i.e. experience of process. Moreover, even if the information about previous design practices is recorded in writing, it is unlikely to be accessed. It is vital to retain this kind of expertise and make it available, or 'more accessible', to the less-experienced designers. Computer tools could be used for this purpose if they are provided with sensible interfaces.

1.3 Inter-disciplinary Design Working and an Intelligent Design Aid

To overcome the problems mentioned within the preceding section and, eventually, to improve the productivity of the design process as well as the quality of the building in terms of human, social, functional and environmental needs, it may be necessary to consider the following matters:

(i) to integrate consideration of the various aspects of a building, i.e. a multi-disciplinary point of view needs to be promoted;

(ii) adequate communication within a design team at an appropriate stage should be achieved particularly during the strategic phase, where the concepts of the building to be designed are developed;

(iii) a computer-based design aid which could allow the design team members to work together, i.e. in an inter-disciplinary manner while utilising the power of sophisticated building simulation programs, would be advantageous;

(iv) it is desirable that the design expertise owned by a handful experienced designers of each discipline is made available to those with less-experienced; and

(v) a computer-based design aid could be utilised to enhance the use of design information, in terms of its access to as well as transfer.

It appears that three subjects of study can be drawn from these matters, namely,

(1) inter-disciplinary design working,

(2) the effective use of design information, and

(3) integrated building design environment and intelligent front end.

In the next three sub-sections, these concepts are discussed with their relevant literature survey.

1.3.1 Inter-disciplinary design working

The word 'discipline' in this thesis means a particular area of study associated with a profession. Generally speaking, an expert usually has specialised skills and knowledge with respect to a particular discipline, and works as a professional in that area, sometimes, in isolation (Figure 1.5 (a)). Since designing a building involves several different disciplines, no single person can expect to cover every aspect of the process with a sufficient level of knowledge on his own [Croome, 1983]. Consequently, various professionals from different disciplines need to be involved. But, if there is no co-operation between these professionals, or only rigid, one-way communication routes exist, it is difficult to fulfil adequately the various design requirements which are interacting with each other (Figure 1.5 (b) and (c)). It is, therefore, important to establish and maintain mutual communication among the disciplines so that co-operation is sustained within the design team (Figure 1.5 (d)).

(a) **Disciplinarity**
specialization in isolation

(b) **Multi-disciplinarity (1)**
no co-operation

(c) **Multi-disciplinarity (2)**
one-way communication

(d) **Inter-disciplinarity**
mutual communication
and co operation

Figure 1.5 Development of inter-disciplinary working: co-operation and communication between the disciplines.

In order to overcome the potential for inefficiency of function, or the danger of failure in the finished building, caused by poor communication and isolation within a design team, inter-disciplinary design methodologies would be advantageous. All the relevant professions would be represented at the inception stage and throughout the 'strategic' phase, working together towards common and agreed goals. While one member of the design team may be elected or naturally assumed to co-ordinate the design team, as shown in Figure 1.6, each participant, be they an architect, quantity surveyor, structural engineer, mechanical and electrical engineer, has an opportunity to understand the client's requirements from the start of the design process. Consequently, every facet of the design problem may be examined in depth in terms of design alternatives as well as regulatory requirements as the process progresses. Appropriate communication between the design team members at crucial design decision stages would be promoted in such a working environment, despite the inherent communication problem that often exists between the disciplines.

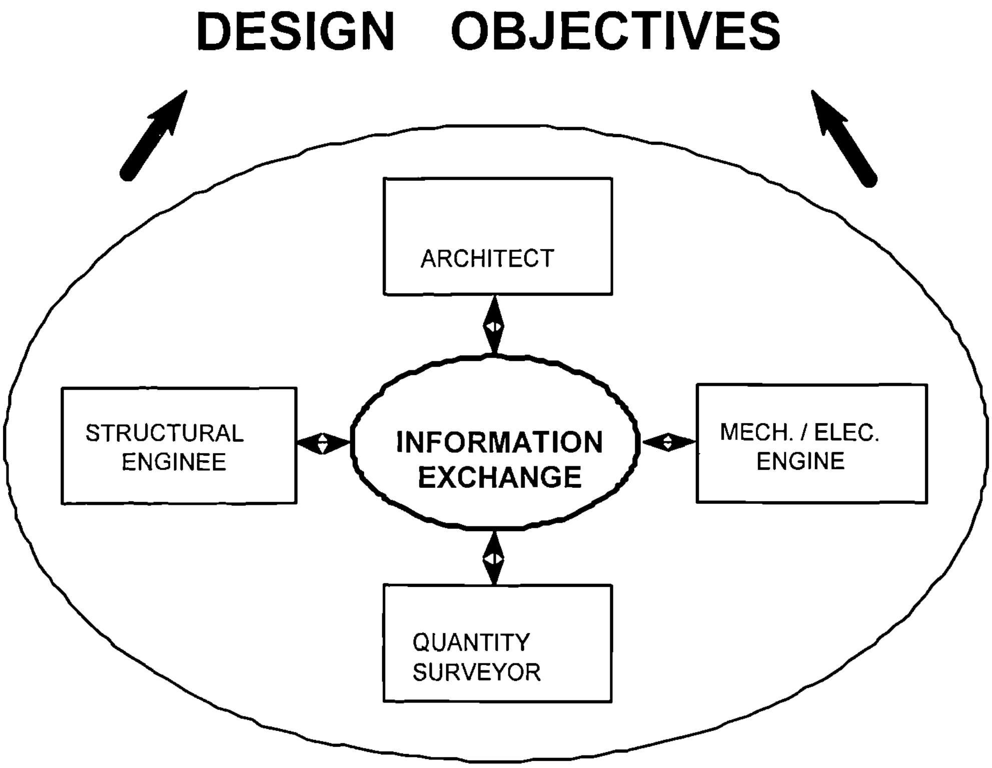


Figure 1.6 Inter-disciplinary design working within a building design team.

Since the 1970s, when the initial energy crisis occurred, energy consciousness has become an increasingly important issue within building design. Because energy transcended many aspects of building design its inclusion as an issue has led to the development of ideas associated with inter-disciplinary working which have been discussed in terms of design team organisation as well as co-ordination within the team [Gray, 1974; Gfeller and Kohler, 1986]. Gray proposed the establishment of permanent multi-professional groups which would be responsible for each job from inception through to the maintenance period. He argued that the client should be involved in the team, together with an architect, structural engineer, mechanical engineer, electrical engineer, public health engineer, interior designer, building surveyor and quantity surveyor, in order to ensure that the full implications of his/her requirements would be understood clearly and to avoid serious disruptions with the design process caused by later changes to the brief. The authors also stressed the importance of team working, involving the client, extending from the pre-planning through to the operation stage (Figure 1.7) [Gfeller and Kohler, 1986].

When considering inter-disciplinary working in terms of the design of the building's internal environment, the co-ordination of the building services with other design aspects is important. Croome discusses the role of building environmental engineers within building design [Croome, 1983]. He considered that their aim should be to balance functional requirements, aesthetics and total cost in building design by employing inter-disciplinary design working and integrated design techniques, through the use of techniques such as cost-benefit analysis and computer-aided design, and by taking a more extensive view of human factors [Croome, 1983].

Although educational courses for such inter-disciplinary working are being provided at some institutes, it may not be easy to put this idea into practice in general terms, because:

- professionals want to be 'experts' within their background, and do not always welcome interaction with other professions, and
- features of the professions differ: the deeper the professionals get involved in their fields, the more difficult it becomes for them to work together, or even communicate with each other, in terms of their languages (vocabulary), willingness and interests [Building Services, 1985].

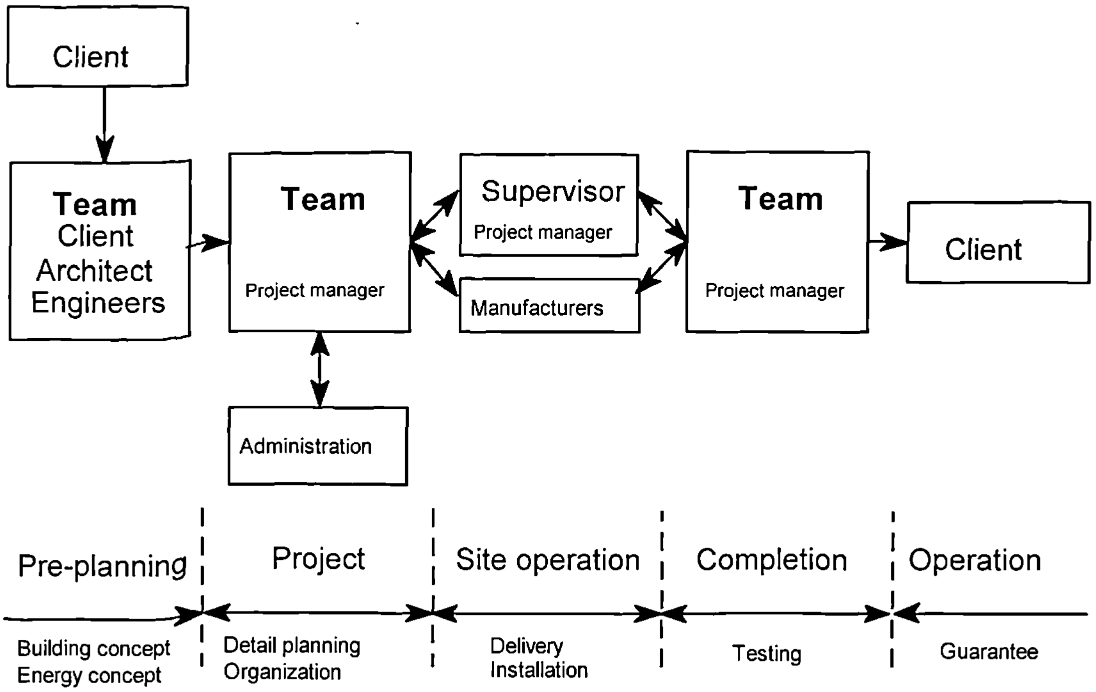


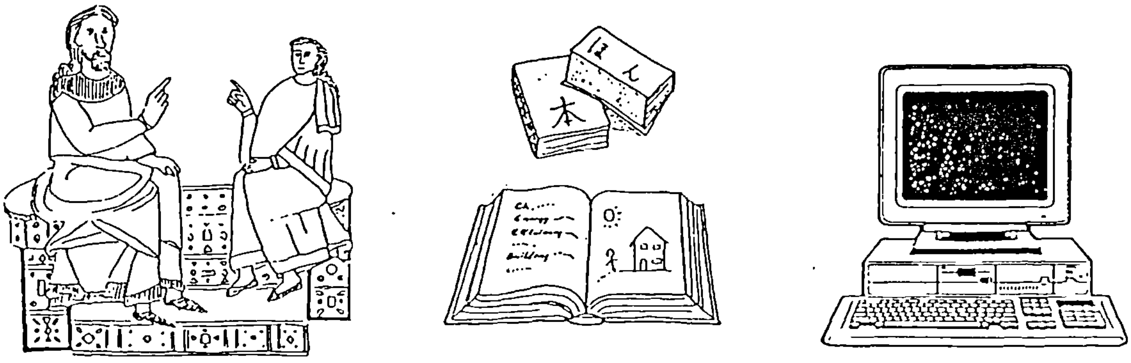
Figure 1.7 Integrated planning: a team working from the pre-planning throughout the operation stage [Gfeller and Kohler, 1986]

Many potential barriers exist to make inter-disciplinary communication and working either difficult or impossible. Some of these relate to attitudes of professional isolationism or considerations of traditional hierarchies and they are often reinforced by fee structures which promote excessive competitions for payments for specific aspects of the finished building. It is to be hoped that changes introduced to the education of these professionals will begin to diminish some of these problems. However, this still leaves the problems associated with inter-disciplinary communication, the binding process for inter-disciplinary working, unresolved. This is a function where the full capabilities of computer environments could be harnessed via an intelligent design aid using the intelligent knowledge-based systems techniques. An intelligent design aid which can cope with all aspects of every discipline could improve the communication between different disciplines at crucial decision making stages. Such a design aid could be used as a search facility, or process checker, which highlights potential problems that may arise from particular decisions.

1.3.2 Effective use of design information

Effective use of design information is another key requirement for improving the productivity of the design process and ensuring the quality of the building. For this purpose, the intelligent knowledge-base systems techniques could be used for handling and transferring extensive design information including both experience and written design data.

Looking at the history of passing on expertise, this seems to have been carried out largely through long apprenticeships lasting for many years, maybe since civilised societies were formed (Figure 1.8 (a)). Then, when printing techniques were invented, books took over much of the role of information transfer, and these days they are one of the most vital information sources (Figure 1.8 (b)) although the apprenticeship of a relatively short time scale may still be a common method of transferring expertise in some areas. The recent development of intelligent knowledge-based systems techniques together with the attributes of multi-media environments seem to provide more effective measures to cope with and transfer the experience gained from previous design practice as well as the huge amount of written data such as Design Codes (Figure 1.8 (c)). It should be possible to construct a computer-base information system which allows the designers easily to access adequate and appropriate information at all stages throughout the design process in a form that is relevant to the project.



APPRENTICESHIP BOOKS COMPUTER TOOLS

Figure 1.8 Means of design information transfer

Lockley et al. evaluated the different media, i.e. handbooks, computer graphic systems, computer database and logic programming, that can be used to convey information to participants within a building design process. As a result it was found that each of these media had both desirable qualities and shortcomings, and, "treated in isolation, none of them provided a wholly satisfactory or efficient means of communicating with architects" [Lockley et al., 1987]. Then they presented a brief for an information transfer system for external envelop design, "the computer-based external wall advisor", by combining the advantages of the database, computer-based drawing system and logic programming. They argued that:

- The way in which information is conveyed should be quick and easy to absorb, especially during the early stages;
- Information should be offered only at the design stage for which it is relevant;
- The information should be authoritative, and wherever possible containing the identity of its source; and
- Graphical representation and checklists are preferred, if possible.

In the context of the building design process as a time-constrained activity, the use of such a computer-based design information system could address the following four functions:

(i) accommodating information access,
(ii) democratising design expertise,
(iii) repository of experience, and
(iv) an educational purpose.

Firstly, the intelligent knowledge-based systems techniques could provide a more effective and convenient way to access design information than the written form. The computer-based information system would select adequate design information, i.e. experience as well as written data, for the design context, and if the system could present the design information to designers in a sensible manner at an appropriate stage, such a design aid would be a useful information resource to improve productivity of the design process.

Secondly, a computer-based design information system could make design expertise belonging to only a handful of individuals available to other less-experienced designers. In other words, it could 'democratise' the expertise, which often appears to belong only to individuals. This means that those who have little experience might not necessarily have to rely upon the presence and availability of their more knowledgeable colleagues, and as a result information transfer could be rationalised. However, this suggests another function for the system as a process checker which would assess the decision made with respect to its information base. Such a system also means that when an individual leaves a practise his experience and knowledge remain within the knowledge-based system.

Thirdly, a computer-based design information system could be a 'repository of expertise' by gleaning design knowledge such as experience of the decision-making process and the performance of previous design solutions, and by formulating it within a knowledge-base. The experience of performance of previous design solutions, in particular, which is often based on the failure of some aspect of actual performance, should be utilised to prevent similar mistakes. The challenge is, therefore, to pre-empt such failures through the use of predictive design aids and some form of checking facility.

Fourthly, and finally, such an information system could also be used for educational purposes if the knowledge about how to carry out the design process is presented with suitable instructions. It should be possible to promote the inter-disciplinary design working by providing experience of the decision-making process associated with it. However, eliciting expertise from designers is a 'bottle-neck' in the development of an intelligent knowledge-based system. The knowledge acquisition, i.e. eliciting expertise and organising it in an appropriate manner, is one of the most challenging subjects in this field.

1.3.3 Integrated building design environment and an intelligent front end

An inter-disciplinary working environment would seek to enhance communication between team members. But, although a number of PC- (personal computer) and work-station-based CAD (computer aided design) systems and validation programs have improved the opportunities for rationalised design activities, most, if not all of them, are too discipline-specific to act to improve the communication between design team members. In addition, the designers often fail to utilise the power of these sophisticated design tools effectively because their user-interface limitation makes them difficult to use. To promote inter-disciplinary design working as well as utilising the power of sophisticated computer-based design tools, an integrated design environment, as shown in Figure 1.9, may be required, which can comprise: (a) a building model, (b) various simulation programs and data bases, and (c) an intelligent front end.

The main intention of such an environment would be to enable design team members to carry out their design activities multi-laterally based upon a common building model which would link to and use existing computer software packages, or 'back-end' programs. The common building model would provide a common structure which would allow specific aspects of the building design to be modelled and examined by the back-end programs. The back-end programs could then execute their validation activities, while maintaining the integrity of the design. The databases would provide design data such as building components for the building models as well as local climate data for simulation. The intelligent front end could be developed to provide a user interface allowing users with different levels of familiarity to utilise the power of the software packages more effectively.

(1) Building models and simulation programs

Computer-based architecture-engineering-construction applications

Holtz [1989] presented the outline of an integrated energy and environmental problem solving system which includes: (a) computer integrated architecture-engineering-construction (AEC) applications that operate in (b) a computer-aided design (CAD) environment as illustrated in Figure 1.10, (c) knowledge-based systems (so-called expert systems) tied to (d) sophisticated energy and environmental analysis procedures and (e) advanced video-graphic display technology. In order to achieve such an integrated system, however, one of the hurdles to overcome is a representation of the building model. Since most computer tools have been developed for particular purposes, the object, i.e. a building design, is simplified and modelled for the specific aspects which the applications accommodate. As a result, the models for these application programs have different data structures, which are mostly incompatible. It is often cumbersome to maintain coherence and consistency between these design models. The development of the integrated design environment would therefore require combining, or integrating, these different building models. Some of the studies related to this aspect are summarised below.

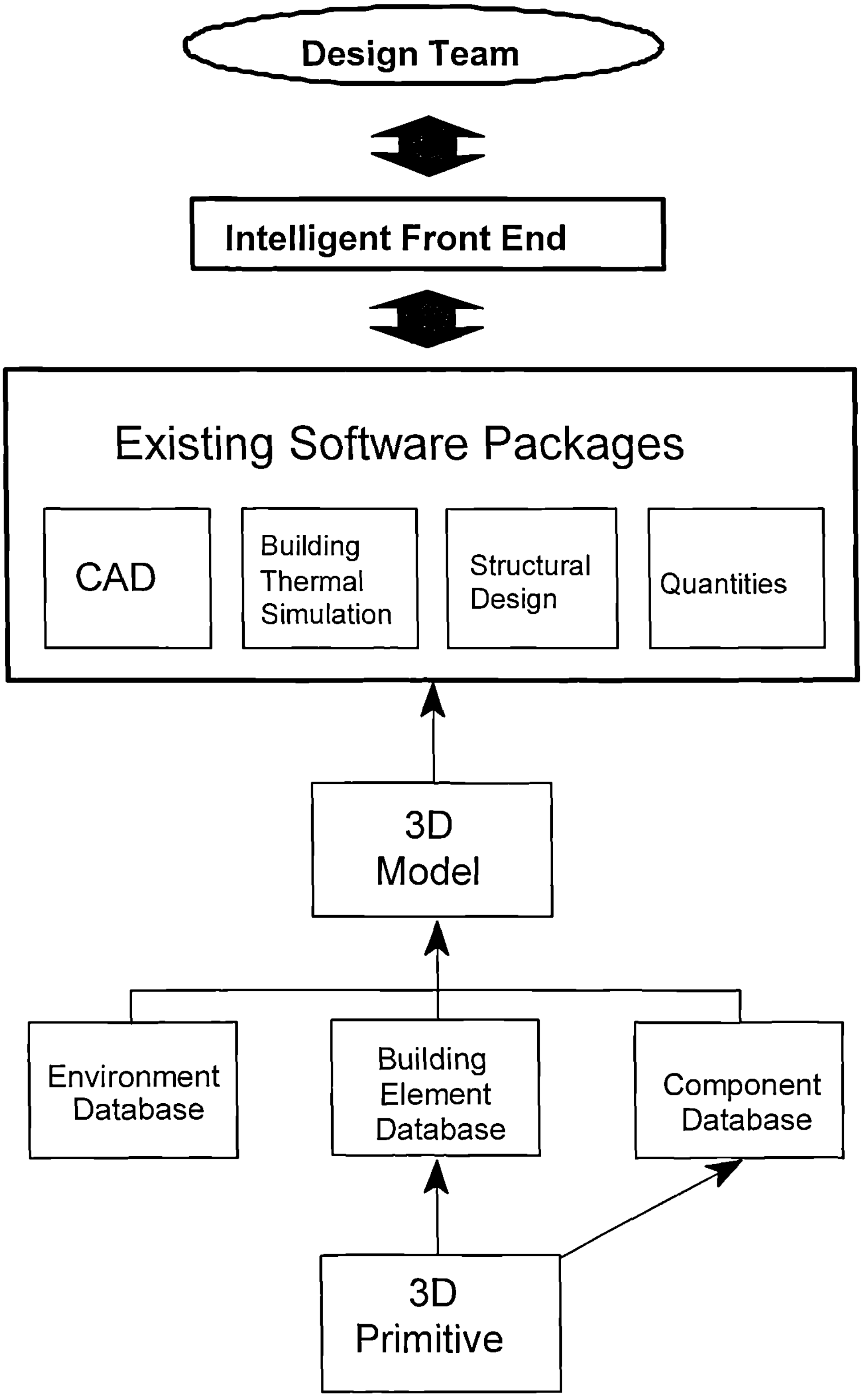


Figure 1.9 Outline of an integrated building design environment

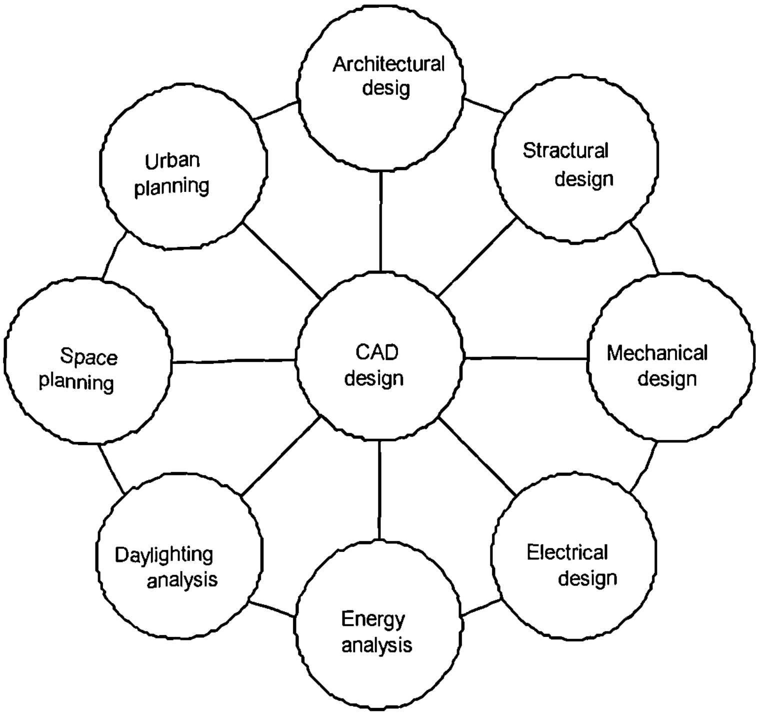


Figure 1.10 Computer-based architecture-engineering-construction applications operating on CAD environment [Holtz, 1989]

IBDS (Integrated Building Design System)

Nagasawa et al. developed an integrated building design support CAD system, IBDS (Integrated Building Design System), for the detailed design stage [Nagasawa, 1989]. This system has three features, as follows:

- It comprises a building model, represented using an object-oriented programming language, and individual design support modules such as building shape design, structural design, cost calculation. As the building model is a common design information source to these individual tools, when the design has been modified from one aspect, e.g. building shape, designers will not be bothered with correcting design data for the other aspects, such as cost.
- The IBDS employs a building model management mechanism to check for any inconsistencies between various aspects of the building model when it is modified.

- In order to support the design activity consistently throughout the detailed design stage, it assumes a standard design procedure.

It is reported that this system could shorten the design period to approximately one twentieth in comparison with the usual method. Although the support which the system provides is limited to a part of the detailed design activities, it is interesting that:

- the several individual design tools are accessing a common building model so as to integrate different aspects of the building design, and
- a standard design process is assumed so that the detailed design activity is rationalised.

COMBINE

One of the attempts to develop an intelligent integrated building design environment is the European Community (EC) initiative project, COMBINE (**COM**bined **B**uilding Models **IN** **E**urope) [Lockley, 1993a]. The concept of the COMBINE project is that different design tools (design tool prototypes: DTPs) would be grouped around a central common data repository, an Integrated Data Model (IDM), and could share and exchange the information about a planned building (Figure 1.11). Such a central data model, i.e. an IDM, holds a generic representation of buildings from which these different design tools can extract their required information of various kinds. The IDM is required to provide the design tools with means for data exchange and also to contribute to the definition of what should be a kernel conceptual schema for the construction industry as well as future intelligent integrated building design systems [Dubois, 1993].

The objective of the earlier phase of the project, called COMBINE I, was to create a conceptual model of the data description of a building that was wide enough to meet most of the building description needs of the six energy-related design and evaluation tools [Lockley et al., 1993b]. A conceptual model was developed by: a) examining the input-output requirements of these design tools; b) identifying entities of a building, its services and the relationships between them; and c) modelling these entities using an object-oriented approach. The function of this conceptual model was to provide the framework that could allow information to be exchanged between different design tools. It was designed to comply with the International Standards Organisation (ISO) STEP (STandard for Exchange of Product data), so that the information exchange takes place using the STEP data file and the EXPRESS data definition language which provides data schema. This conceptual model is now being improved and will be implemented in the form of an Object Database [Dubois, 1993; Lockley et al., 1993b]. Although Lockley et al. have demonstrated the feasibility of this approach through the development of an aspect model which can support multiple design tools, they also found that the problem of the management of transactions within the aspect model would be too complex to manage any change of data and would be unstable when a number of design tools were working concurrently [Lockley et al., 1993b].

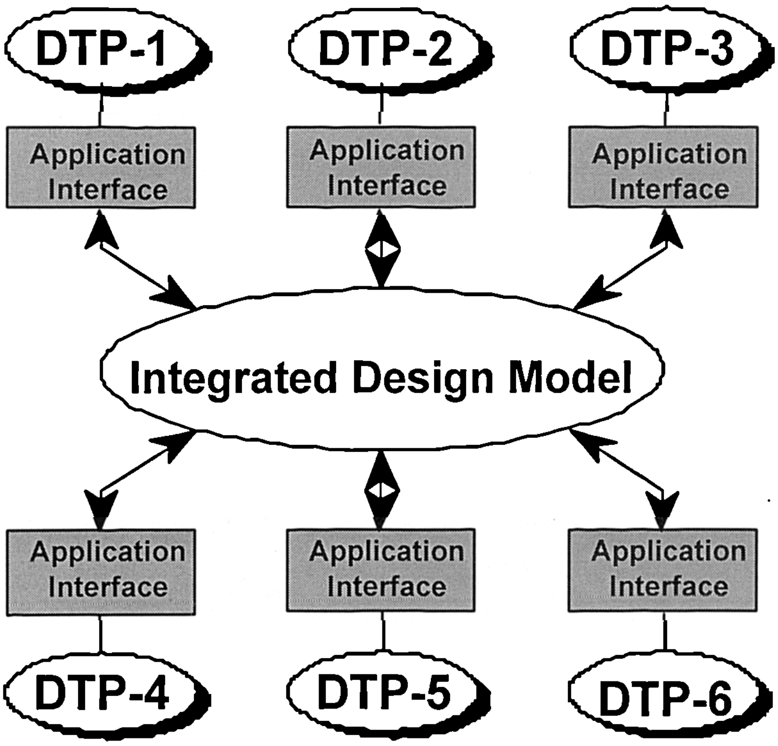


Figure 1.11 Global architecture of the COMBINE Project:
Data exchange between the Integrated Data Model and Design tool prototypes (DTPs). [Lockley, 1992; Dubois, 1993]

(2) Intelligent front end

Intelligent Front End

One of the major barriers to the effective use of design tools is the shortcomings in their user-interface. The user-interface-limitation appears to arise from the expertise which needs to be developed to be able to use the design tools and the variety of user type and the range of their experience. In the former case a user of sophisticated application programs is required to possess a high level of knowledge about how to use them and professional experience in terms of data input. This is caused by the conflict between the necessity for the computer model to be comprehensive and adequately to represent the complex real world and the user requirements that the tools should be simple, straightforward and easy to use. The second is that the requirements of the interaction between a user and a design aid should differ according to the user's ability and objectives: the users who use it infrequently for appraisal of the performance of their design may require only a concise summary of the results, whereas those who are deeply involved with using design aids for their research, for example, may often need all the results of validation available and capable of being displayed in juxtaposition with other data.

In order to overcome the user-interface problems, Clarke et al. attempted to develop an intelligent front end (IFE) using intelligent knowledge-based systems (IKBS) and human-computer interface (HCI) techniques [MacRandal, 1987; Clarke et al, 1989a; Clarke and MacRandal, 1991]. The IFE is a user-interface which would incorporate a significant level of knowledge in relation to the domain being addressed (building design), the applications being used (energy simulation) and the user's objectives and machine interaction preference. The knowledge would include that concerned with the domain as well as the context in which the application program is being used, so as to define the mapping from any user's conceptual model of the domain to the data and control requirements of a targeted application.

The IFE would consist of several co-operating modules organised around a central communication module, the Blackboard, as shown in Figure 1.12. There are two classes of these modules: those at the user-end (i.e. the Dialogue, Knowledge and User Handlers) concerned with extracting the building and appraisal definitions from the user; and those at the back-end (i.e. the Appraisal, Data and Application Handlers) concerned with creating the input data and controlling instructions to 'drive' the application program. The first group of modules would tailor the user's level of experience and performance history by keeping track of the user's progress, whereas the second group of modules would prepare and provide an appropriate data set to the application program. The Blackboard stores the data representing the current state of the problem definition, as well as acting as a communication centre for the modules. In their prototype system, called IFe, the Blackboard has been developed and some of the modules have been implemented using Prolog. The ESP, a system for the simulation of the energy behaviour of buildings [Clarke, 1989b], has been chosen as a back-end program.

It seems that communication via the Blackboard could be an effective approach to cope with the complexity of the interaction between the user and back-end processor. Further study needs to be carried out, however, in order to deal with the difference of user types and provide adequate mapping from the users' conceptual model of the domain to the data and control requirements of the back-end programs. It will also require a great deal of effort to acquire the knowledge which accomplishes the objectives of the IFE.

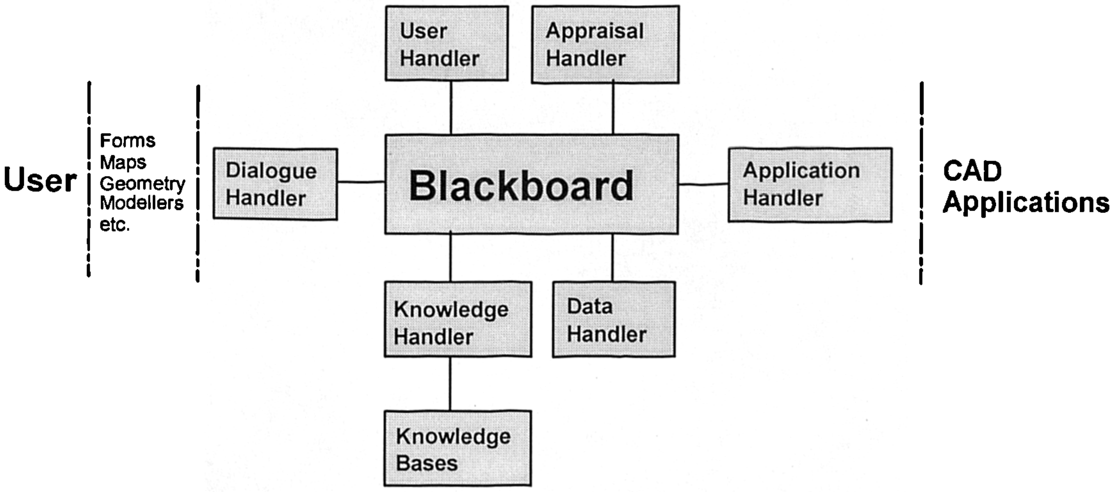


Figure 1.12 Architecture of the IFE [Clarke et al., 1989, 1991]

Energy Kernel System

In the meantime, in order to optimise a building energy system which is inherently dynamic and non-linear, the subject of building simulation, particularly the integrity of the underlying mathematical models and their validation, has received growing attention in recent years. Clarke et al. [1992] have explored the feasibility of developing an advanced program building environment, termed the Energy Kernel System (EKS). The EKS is to provide a platform which facilitates a coherent approach to development, validation and maintenance of computer programs for building energy/environmental prediction without the need to work with a source code. This research includes a feasibility study of adopting the object-oriented programming paradigm in the representation of the computational methods underlying building energy/environmental prediction models, and their underlying data structure.

Essentially, the EKS contains a set of class definitions corresponding to the building and thermodynamic domain. Each class handles one particular aspect of the building performance prediction process. These classes have been organised into a 'Taxonomy', which specifies how the classes inter-relate and defines the information flow between them. They can be considered as the basic building blocks from which a wide range of modelling programs may be built. It was reported [Clarke et al. 1992] that an EKS demonstration system which supports the construction of a range of models from a simplified calculator to a state-of-the-art simulator had been developed using an object-oriented programming language, and also that the technical feasibility of applying the object-oriented programming approach had been proven.

A notable feature of the EKS concept is that it would allow designers to participate in the building tool creation process by making advanced developments of the building energy simulation accessible to the end users. To achieve this ambition, however, further research is required in terms of the computational methods underlying building energy/environmental prediction models, as well as the practical usage of the EKS within an actual building design context.

1.4 Aim and Approach of the Project

Both the promotion of inter-disciplinary design working and the effective use of design information appear to be vital in order to improve the productivity of a building design process as well as attaining a quality-assured building design. It is proposed that inter-disciplinary design working and more effective use of all information could be achieved via the use of intelligent knowledge-based systems (IKBS) techniques (Figure 1.13). This study eventually seeks a way to enhance opportunities for inter-disciplinary building design working in terms of the development of a descriptive framework for the process and an intelligent design aid linked to it.

This project has two main objectives. Firstly, it aims to describe a framework for inter-disciplinary design working with particular reference to daylighting and lighting design. To promote inter-disciplinary design working particularly during the early 'strategic' phase of the process, it seems to be important to attempt to describe such design working in a rational form. It is felt, however, that the scope of this should be restricted to consideration of the relationships between various disciplines in relation to particular aspects, rather than the building design as a whole, in order to keep the project to a manageable size. The building design process is therefore studied with particular reference to daylighting and lighting design aspects, and the framework derived from such study is developed in the form of a checklist. Using the checklist which is based upon the framework, the designers can consider various aspects of their design as well as the implications of the choices they make regarding crucial decisions during a building design process. This could encourage the design team members to communicate with each other at pertinent stages, so that inter-disciplinary design working could be promoted.

Secondly, the objectives of this project also include developing an IKBS which demonstrates the viability of a checklist approach for inter-disciplinary design working, so as to examine the validity of an IKBS technique for this particular application. The development of such an IKBS is not intended to automate the building design process, but that decision-making should remain with the designers. Instead, the IKBS would be a design aid which is, based upon the checklist, capable of verifying designers' decision-making activities. In this sense, such an IKBS could act as a 'process checker' which would help to reduce errors of omission during thc course of the design process. At the same time, the development of such an IKBS should be concerned with information and experience transfer to less-experienced designers. In this sense the IKBS is also a design aid which allows the designers to access adequate design information at a pertinent stage in an effective way, i.e. an 'information resource'.

An IKBS which can act as both a process checker and an information resource may be eventually form the basis for an intelligent front end for design software by combining with other design tools, such as CAD and existing simulation tools, for the further work. Developing such an integrated design tool is, however, out of the scope of this study.

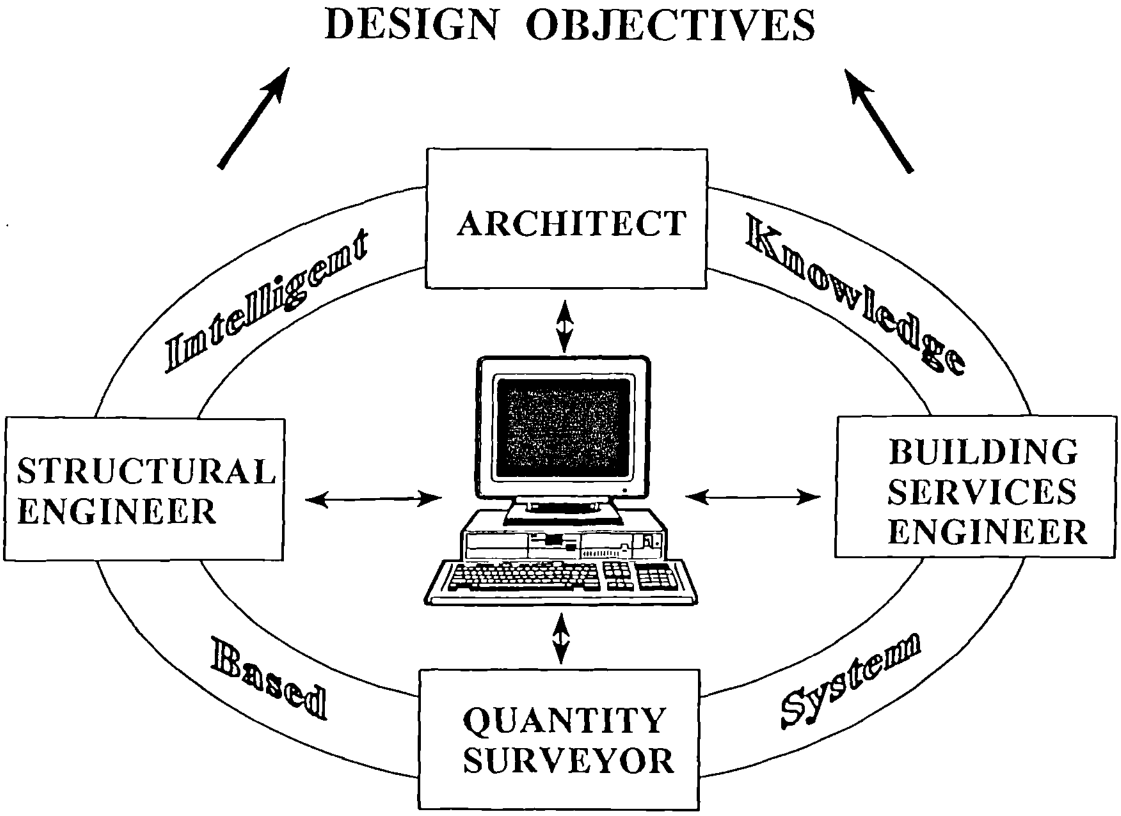


Figure 1.13 An intelligent knowledge-based system for inter disciplinary design working and design information transfer

To attain these objectives, the following approach has been undertaken:

(1) Daylighting and lighting design aspects

The building design process is studied with particular reference to the daylighting and lighting design aspects. The study of the building design process is based on the Royal Institute of British Architects, RIBA, *Plan of Work* and British Standard BS82207 '*Energy Efficiency in Buildings*' with regard to low energy design, which involves case studies of building design activities. Other published materials, such as British Standard BS8206 '*Code for Interior Lighting*' and CIBSE Application Manual '*Window Design*', are used to supplement daylighting and lighting design aspects.

(2) Rational description of the building design process

To develop a framework for inter-disciplinary design working, it is felt that the building design process needs to be rationalised in terms of the decision-making activities of all those professions within it. A rational description of the design activities is proposed which introduces *design variables* to represent the parameters involved within the process. This rational description allows a framework for inter-disciplinary building design working to be developed by defining such *design variables* and examining the relationships between them.

(3) The knowledge-based representation and a checklist for the building design working

Referring to the published materials mentioned above, a wide range of information relating to inter-disciplinary design working with particular reference to daylighting and lighting aspects has been collected and collated. Such information has been collected into units of knowledge. The relationships between the *design variables* are then associated with the units of knowledge which describe them, and eventually a framework for inter-disciplinary building design working with particular reference to daylighting and lighting design aspects is developed. A checklist is developed based upon this framework, indicating what needs to be considered as well as the relative timings of the various decisions that are made as a design progresses.

(4) Developing a demonstration system using an IKBS technique

Several intelligent knowledge-based system techniques such as the rules and objects, and their use are discussed in conjunction with the development of an intelligent knowledge-based system for inter-disciplinary design working. The production, or rule-based, system has been chosen to develop a demonstration system which can be used as an 'information resource' and a 'process checker'. Such an IKBS has been developed based upon the checklist, using a commercially available expert system shell, *Leonardo 3*.

1.5 Structure of this Thesis

[Chapter 2]

Chapter 2 considers the building design process. The building design process is addressed in terms of the Royal Institute of British Architects, RIBA, *Plan of Work* stages, and design tasks involved in the early strategic phase are described. A design approach for energy efficiency in buildings is then explained based upon British Standard BS8207, and the energy implications of daylighting and lighting design are also discussed.

[Chapter 3]

In Chapter 3, a rational description of design activities is discussed in terms of both production and evaluation of design solutions, whilst referring to the analogy between design and problem-solving and logic. The role of stereotypes is taken into account particularly with regard to the production of a design solution. It is then proposed to describe the design activities in terms of three kinds of parameters, i.e. information including requirements and constraints, design decisions which describe an artefact and performance characteristics, and then it is considered that the design activities involve "*mapping*" between information, design decisions, and its performance characteristics. Such a rational description will be the basis of a framework for the building design process developed in a later chapter. It is also argued that the mapping could be represented by "knowledge" which will lead to a knowledge-representation of the process.

[Chapter 4]

This chapter focuses on the development of a framework for inter-disciplinary design working with particular reference to daylighting and lighting design aspects. The building design process is described in a hierarchy comprising a set of sub-problems ("*design issues*") and design activities ("*design tasks*") which originate from *design issues*. The *design variables* are defined in association with these *design tasks* which are identified with particular reference to daylighting and lighting design aspects. Adopting the rational description of design activities proposed in the previous chapter, a framework is then developed examining the relationships between these *design variables*. On the basis of this framework, a checklist taking account of the needs of inter-disciplinary building design working is developed using the knowledge extracted from published materials, including the Chartered Institution of Building Services Engineers, CIBSE, Application Manual "*Window Design*".

[Chapter 5]

In Chapter 5, a computer-based design aid for inter-disciplinary building design working is discussed in relation to the application of intelligent knowledge-based systems (IKBS) techniques. The required functions of the IKBS are considered to enhance the effective use of design knowledge, as well as promoting inter-disciplinary working.

[Chapter 6]

This chapter explains the IKBS techniques used and the development of a prototype intelligent knowledge-based system, in terms of the use of a commercially available expert system shell, *Leonardo* 3. The basic operation of the prototype system is described, and then its capabilities are assessed in relation to the requirements addressed in the previous chapter.

[Chapter 7]

Chapter 7 draws conclusions from the study of the development of a framework for inter-disciplinary design working and the knowledge-based system developed based upon the framework. It also discusses the promotion of inter-disciplinary building design working, as well as the application of the intelligent knowledge-based system techniques, and finally, addresses further work for the future.

Chapter 2

Chapter 2

BUILDING DESIGN PROCESS

This chapter is to provide a basic understanding of the building design process and study design tasks in relation to the Royal Institute of British Architect, RIBA, *Plan of Work.* In the first section, the RIBA *Plan of Work* is briefly explained, and the building design process, the early "strategic" phase in particular, is presented in terms of the *Plan of Work* stages. In Section 2.2, a design approach for energy efficiency in buildings is described based upon British Standard BS8207, in relation to the *Plan of Work* stages, particularly its early 'strategic' phase. Since this project studies the building design process with particular reference to daylighting and lighting aspects, this section also discusses their energy implication in relation to the building design process. (The fundamental issues relating to window and artificial lighting design process are explained in terms of energy efficiency and environmental comfort in Appendix B.) In order to study the design activities in conjunction with the design approach for energy efficiency in buildings, a case study was carried out. The result of the case study is summarised in Section 2.3. (Full description of this case study can be found in Appendix C of this thesis.)

2.1 The RIBA *Plan of Work* and Building Design Process

2.1.1 The RIBA *Plan of Work*

As discussed in Section 1.2.3 of Chapter 1, building design procedures can be considered to follow the basic process outline described by the Royal Institute of British Architects, RIBA, *Plan of Work*. This describes a planned and logical sequence of events arranged in stages, delineating all the management tasks and design work in a project programme, from the initial contact between a client and an architect to the point when the building is completed and in use.

The background of its development, and its status, is described in its preface as follows [RIBA, 1988, p.9]:

> "The RIBA *Plan of Work* was devised in response to the need to establish and consolidate building procedures after the pressures and ad hoc policies of the 1950s, to lift the morale of the building industry as a whole and to reaffirm the credibility of the architectural profession. It set out a *modus operandi* for administering projects, divided into sequential 'work stages'. Over the years, the *Plan of Work* became widely accepted by the building industry and the associated professions. It took on an identity of its own and became a recognised element in architectural education as well as a point of reference in professional disputes and litigation. .... The *Plan of Work* continues to be recognised throughout the industry as the 'model' way to administer a job, ... and its use is recognised as evidence of systematic project administration in the context of quality assurance assessment."

According to the RIBA *Plan of Work*, after the client has identified his building needs and what resources he has available, and has selected an architect, the work involved in building design and construction falls into the following broad sections:

- Inception
- Design and Production information
- Contract procurement
- Project planning and site operation.

The RIBA *Plan of Work* subdivides these operations into a programme of 12 stages (see Figure 2.1) which assumes that time and circumstances allow the stages to follow one after the other, and that competitive tendering procedures are used [RIBA, 1988, p.15]. The RIBA *Plan of Work* stages start with early briefing and conclude with feedback in use, and they are briefly described as follows [RIBA, 1988, p.16-17]:

A. Inception

Client establishes basic requirements, cost ranges, timetables etc. He appoints architect and principal consultants. Basic project organisation is established.

B. Feasibility

The design team is organised. The brief is developed as fully as possible. The site, legal and other constraints are studied. Alternative design options are considered. The client is advised about the feasibility of the project in functional, technical, financial and contractual terms. His decision is sought on how the project is to proceed.

C. Outline proposals

The brief is further developed in line with the general approach to layout, design, construction and services. A cost plan is established. The client is asked for his authoritative approval on how to proceed.

D. Scheme design

The brief is completed and architectural, engineering and services designs are integrated. The cost plan, overall programme and outline specification are developed and planning and other approvals applied for. A report is submitted to the client for his approval.

E. Detail design

The team designs, co-ordinates and specifies all parts and components, completes cost checks and obtains client's approval of significant details and costs. Specialist tenders may be sought.

F. Production information

The team prepares working drawings, schedules and specifications and agrees with the client how the work is to be carried out. Specialist tenders may be sought.

G. <u>Bills of quantities</u>

Bills of quantities are prepared and all documents and arrangements for obtaining tenders are completed. Specialist tenders may be sought.

H. <u>Tender action</u>

Main contract tenders are obtained by negotiation or competitive tendering procedures. The client is asked to agree that suitable tenders are accepted.

J. <u>Project planning</u>

Contract documents are processed. The contractor receives information needed to plan the work. The site inspectorate is briefed and all roles are defined. The site is made available for work to start.

K. <u>Operations on site</u>

Contract is administered and contractual obligations fulfilled with progress and quality control monitored. Financial control, with regular reports to the client is maintained.

L. <u>Completion</u>

Project is handed over for occupation. Defects are corrected, claims are resolved and final account is agreed. Final Certificate is issued.

M. <u>Feedback</u>

The performance of the building and the design and construction team are analysed and recorded for future reference.

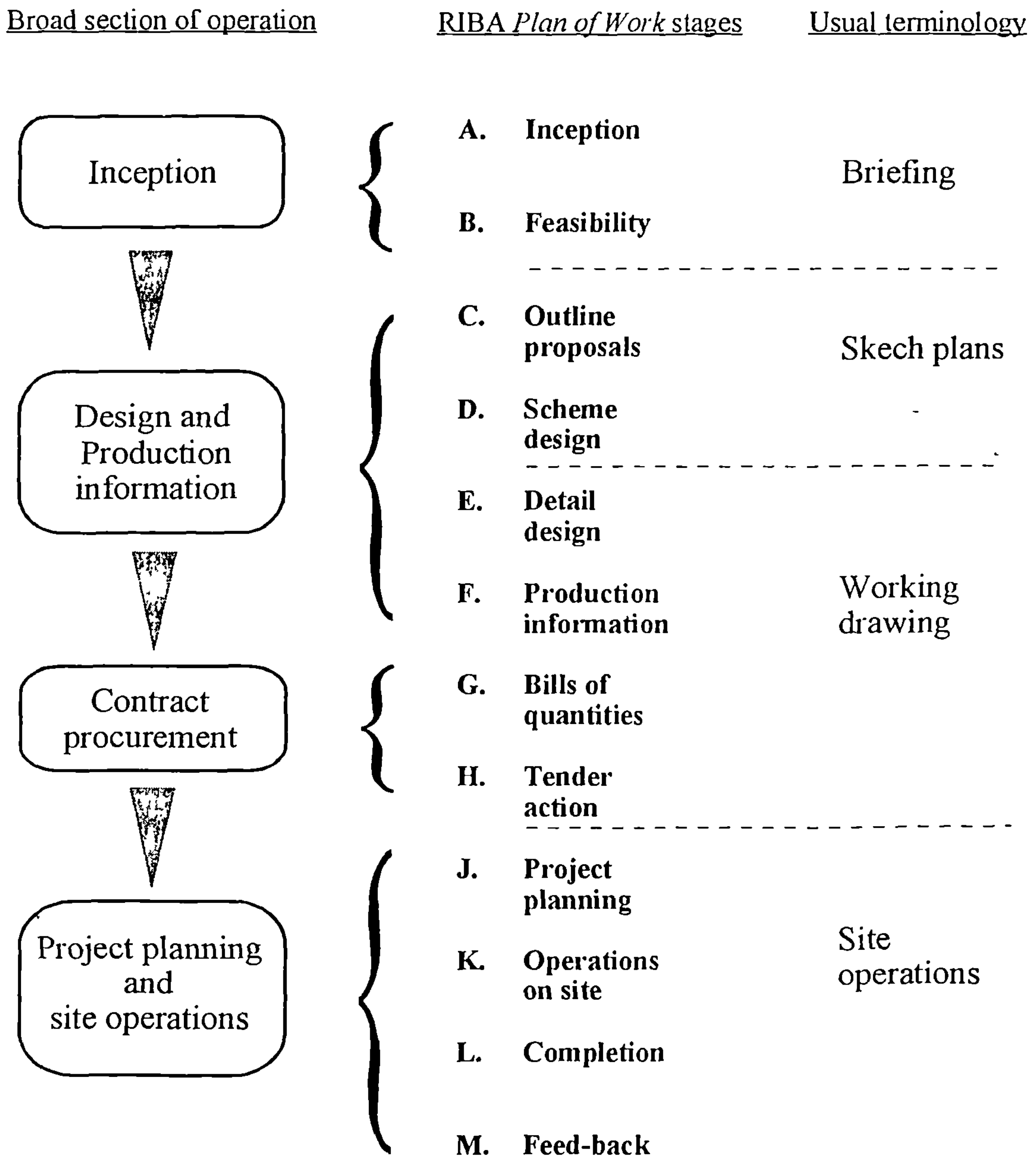
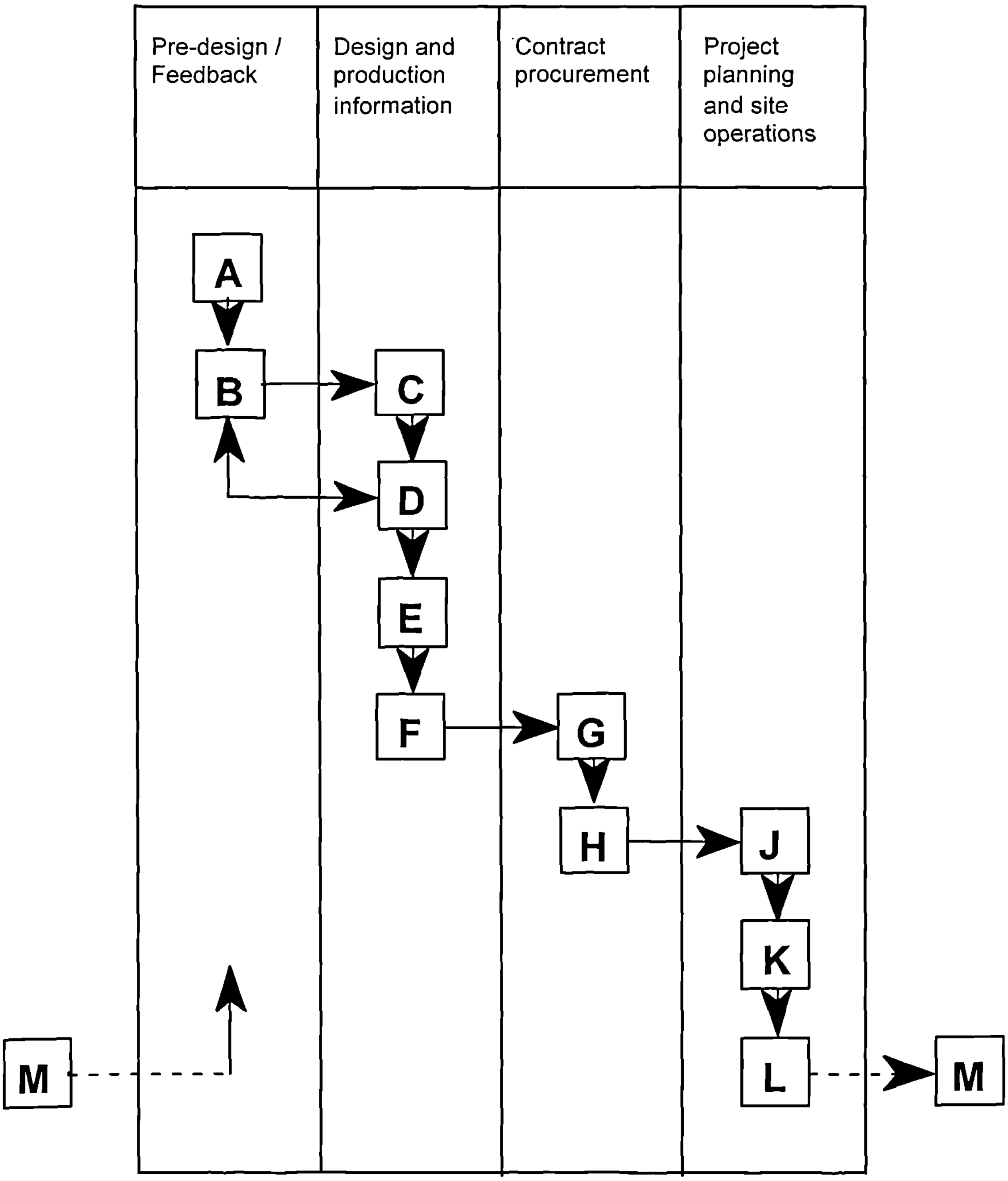


Figure 2.1 Outline of the RIBA *Plan of Work*: Broad sections of building design and construction work are subdivided into 12 work stages.

Figure 2.2 illustrates a traditional sequence of the RIBA *Plan of Work* stages. It shows how the four main sections of work can overlap. It is recognised that there are inevitable jumps backwards and forwards among the stages, but the *Plan of Work* itself follows a completely linear progress. It should be understood that the RIBA *Plan of Work* describes the products of the process rather than the process itself. In other words, the RIBA *Plan of Work* can only depict the stages in any design project at which decisions are made, not a pattern of decision-making. There are circumstances which will require variations to the procedures, because of pressure to achieve rapid completions and/or of the increasing complexity of building technology, for example. The RIBA *Plan of Work* can, however, accommodate the variations by only changing the sequence of the stages, but the detailed actions within each stage remain basically the same. It is therefore "perhaps more an accurate guide to when sections of design are finally completed, rather than a description of when an element of the design is actually considered" [Mackinder and Marvin, 1982, p.44].



The dotted lines on this Figure are a reminder that during the early stages the processes of developing and refining the brief and the design are cyclical.

Aspects of the design will need to be 'frozen' in increasing detail at each stage. Everyone must be aware that subsequnt changes may result in delays and extra cost.

This Figure shows how the four main sections of work can overlap.

Figure 2.2 Traditional *Plan of Work* sequence
[transformed from Fig. 0.2.1 of the RIBA *Plan of Work*]

2.1.2 Outline of the building design process described by the RIBA *Plan of Work*

This study concerns mainly with the design process, which correspond to the first half of the work involved in the development of the building design. In this thesis, therefore, the building design process is considered to involve the first 6 of the RIBA *Plan of Work* stages, i.e. '*inception*', '*feasibility*', '*outline proposals*', '*scheme design*', '*detail design*' and '*production information*'. It is generally recognised that the design process will follow this broad framework. The research of Mackinder and Marvin observed that:

> In all the projects we examined, the designers concerned tended to develop a broad outline of the type of building they considered appropriate in response to their clients' initial briefing, and their own reaction to the site conditions. This is broadly consistent with the recommendations for Stage B (*feasibility*) and C (*outline proposals*) of the RIBA *Plan of Work*" [Mackinder and Marvin, 1982, p.44].

The RIBA *Plan of Work* could show a basic framework for the building design process as a logical sequence of events. Some architects may not adhere to the detailed plan rigidly, but most work largely to the general headings, as payment according to the RIBA Scale of Fees is organised around these stages [Mackinder and Marvin, 1982, p.6]. Concerning these first 6 stages, more explanation is given below, which is based upon the *Architect's Job Book* Volume 1: *Job Administration* [RIBA, 1988], where the *Plan of Work* is described. Each stage is explained in terms of:

(a) the purpose of work within the Stage,
(b) tasks to be done, and
(c) product of the Stage.

A. Inception

(a) Purpose

This is a very early stage where general outline of requirements and plan future action is prepared.

(b) Tasks to be done

After the first meeting between a client and a designer, often an architect, the client's needs are clarified. The client's basic requirements, including cost range and time table are discussed, and suitable means of achieving them are suggested. The context of a scheme is established.

(c) Products

By the end of this stage, the client's initial brief has been established which includes the client's policy and general requirements such as:

- the aim of the project,
- financial limits,
- time table.

The context of the scheme have also been established, concerning:

- internal and external constraints
- legal aspects, e.g. Building Regulations
- technical problems
- site selection (physical and statutory constraints).

B. Feasibility

(a) Purpose

This stage aims to provide the client with an appraisal and recommendation in order that he may determine the form in which the project is to proceed, ensuring that it is feasible functionally, technically and financially.

(b) Tasks to be done

The first element of this process is to evaluate the client's initial brief: whether it provides an adequate statement of his requirements. Then, further information may be obtained as necessary to establish and develop a brief.

To determine the feasibility of the project, studies are carried out on the client's requirements concerning functions, quality, priorities, client consideration and user consideration. Site conditions, planning, design and costs are also studied, and then a brief is established. During the course of these studies, a civil/structural engineer will advice the architect about site and local conditions, such as soil and geological factors, and suggest appropriate types of foundation and structure. Mechanical and electrical engineers will analyze conditions and information, such as climate conditions and problems of emission, to establish preliminary environmental requirements. They will also indicate possible systems in relation to the building forms and types being considered.

The brief is considered with the design criteria, such as *town and country planning*, *Building Regulations*, structural services engineering consideration, and unifying aesthetic concepts, and developed considering alternative design options. The design and construction approaches are appraised with particular reference to their cost implications. Approvals under building acts or regulations, and other similar statutory requirements, need to be obtained. The results of the consideration in turn influence the brief, which is adjusted accordingly. This cyclic process is repeated in progressively greater detail until the end of Stage F.

(c) Products

The implications upon the building construction of environmental standards, the preliminary design criteria and the identification of the need for research are established. A strategy for developing the brief and related information is establish through design team consultation. An appraisal and recommendations are provided, ensuring that the brief is feasible functionally, technically and financially.

C. Outline proposals

(a) Purpose

The purpose of this stage is to determine the general approach to layout, design and construction, in order to obtain authoritative approval of the client on the outline proposals and accompanying report. It is crucial at this stage to design within the approved budget, particularly where services systems are a significant proportion of building costs or where the design is essentially innovative.

(b) Tasks to be done

Further studies on user requirements, technical problems, planning design and costs are carried out to extend design data and reach decisions. The studies may involves as follows:

- study of space distribution and the consequent functional and circulation problems
- Study of effects of planning, physical & other constraints
- investigating alternative solutions and discussing functional implications with client as necessary
- preparation of outline schemes, including critical dimensions.

The brief expands as the scheme develops. Design concepts including structure and services are developed. Here, the civil/structural engineer will work with the architect to develop structural concepts, as the layout, design and form of construction evolves. The mechanical and electrical engineers assist the architect in deciding the building's orientation and its envelope according to environmental factors. They must liaise effectively with all members of the team to evolve services systems appropriate to performance, cost and cost in use with alternative building arrangements. The brief is then reviewed in relation to the client's policy and priorities, project costs and building requirements.

(c) Products

An integrated approach to layout, design, construction and services has been developed, so that structural and services design is determined to meet performance standards, environmental provisions, the budget proposed in a way which can be integrated into the overall design concept. Outline proposals and an approximation of the construction cost have been prepared for the client's preliminary approval.

D. Scheme design

(a) Purpose

The purpose of this stage is to complete the brief and decide on particular proposals, including planning arrangement, appearance, constructional method, outline specification, and cost, and to obtain all approvals.

(b) Tasks to be done

A scheme design is developed from the outline proposals, taking into account amendments required by the client. Construction methods, services schemes, outline specifications for all disciplines and related cost studies are coordinated.

The architect must ensure that structural constraints are compatible with the space and access requirements of the services installations. The civil/structural engineer will advise the architect on structural solutions and criteria. Decisions have to be made on the services layouts and their coordination within the building structure, general ceiling, floor and wall layouts, and access for commissioning and maintenance. The mechanical and electrical engineers will coordinate the services and building arrangements within the constraints set by the architect and structural engineer. They must liaise closely with the architect on all services aspects including the location of equipment and plan services voids, building tolerance and access for maintenance and repairs. The engineers will also establish final design and performance specification.

A cost estimate is undertaken. The quantity surveyor will collaborate with the architect and consultants to develop and refine cost forecasting as the design evolves.

(c) Products

Contributions to overall design and cost plan have been coordinated and finalised, and full design proposals have been consolidated. They include final development of the brief, full design of the project by architect, preliminary design by engineers, preparation of cost plan, and a full explanatory report. The scheme design illustrates the size & character of the project in sufficient detail to enable the client to agree the spatial arrangements, materials and appearance.

The brief cannot be modified after this stage without causing delays and additional cost / fees. Any changes after this stage to the brief must be avoided.

E. Detail design

(a) Purpose

Moving from the strategic phase into the tactical phase, this stage aims to obtain the final decision on every matter related to design, specification, construction and cost.

(b) Tasks to be done

Full design of every part and component of the building is developed by collaboration of all members concerned. The following issues may be reviewed during this stage:

- structure dimensions and profiles against finishes dimensions, services zones and openings and building elements, including tolerances;
- services layouts, spaces, routes, duct ways; access locations; coordinated locations; dimension details related to builders' work and building tolerances.

The design is also reviewed against performance specifications. The architect will liaise with the engineers to ensure proper integration of structural, services and building fabric considerations as required and through design team meetings.

(c) Products

Detailed design of the building have been completed with all its elements, construction and services systems, including coordination of builder's work for services and specialist installations. Cost checking of designs has also has been completed.

The design is now established. From now on any changes, even apparently minor ones, may result in abortive work and may cause delay and extra cost.

F Production Information

(a) Purpose

The purpose of this stage is to prepare production information and make final detailed decisions to carry out work.

(b) Tasks to be done

Final production information, i.e. drawings, schedules and specifications, is prepared. The following tasks may be carried out within this stage:

- coordination of construction, services and other specialist installation;

- preparing the programme for production drawings, schedules, drafts for preliminary specifications;
- preparation of production information including drawings, schedules and specification of materials and workmanship;
- providing information for bills of quantities to be prepared.

(c) Products

All information has been gathered in sufficient detail to enable a contractor to prepare a tender. Detailed drawings and specifications have been prepared. Decisions have been made to enable specialist sub-contract tenders to be formulated.

2.2 Energy Efficiency in Buildings

In the UK, about half of the fuel and electric power that is used is consumed in buildings [BS8207, 1985]. Efficient use of energy is one of the most important issues in the design and management of buildings. The British Standard BS8207 '*Energy Efficiency in Buildings*' concentrates on how to make buildings energy efficient, through good design practices and by careful management and use. Nevertheless, energy conservation is only one of the requirements which a building need satisfy: the function for which it is used and its appearance and general economics have also to be taken into account. The designer has to produce a balanced solution of which energy conservation measures are an integral part.

BS8207 aims to promote energy efficiency in buildings and to provide a basis on which the designers of buildings and their clients can work to achieve this aim, by giving recommendations for the main procedures to be followed to obtain the efficient use of energy in the design and management of buildings. In this section BS8207 is briefly explained, concerning the design of new buildings in particular.

2.2.1 Procedures for energy efficient building design

In order to achieve the efficient use of energy in the design and management of buildings, BS8207 suggests that the following procedures should be followed.

(1) Adoption of a method for estimating the <u>energy requirement</u>.

The energy requirement should be established. When it is established, a calculation procedure should be used which takes into account at least following factors [BS8207, 1985: Clause 4]:

(a) required environmental conditions and periods of use,
(b) climate conditions,
(c) thermal transmittance of each part of the enclosure of the building,
(d) thermal response of the building's main constructional elements,
(e) rate of air change,
(f) effect of glazing on lighting use,

- (g) effects of incidental gains (e.g. occupants, lighting, solar gain),
- (h) effects of shading,
- (j) effects of controls on the main energy using services,
- (k) efficiency of the equipment.

(2) Establishing the energy targets for the comparison of design options.

The purpose of an energy target is to provide a yardstick against which to compare the performance of design options (whether estimated performance as in the case of design studies or measured performance when managing an installation) so that judgement can be formed of the quality of performance expected or achieved [BS8207, 1985: Clause 5].

(3) Assessment of the cost-effectiveness of the proposed expenditure.

Methods for assessing the cost-effectiveness of energy proposals should take account of the following [BS8207, 1985: Clause 6]:

- (a) capital costs;
- (b) periodic charges and their timing;
- (c) value of benefits and their timing;
- (d) discount rate(s);
- (e) the period of time over which costs and benefits are to be considered.

The economic objective is normally either:

- (a) to achieve a required return on investment;
- (b) to get the best return for a fixed budget;
- (c) to achieve a stated standard of performance at least cost; or
- (d) to meet some other economically measurable criterion.

(4) Taking measures for efficient energy management.

The measures for efficient energy management may involve [BS8207, 1985: Clause 7]:

- (a) arranging energy-using services in zones, so that the controls can respond effectively to changes in occupancy and load;
- (b) Providing appropriate controls to permit economic regulation of all energy-using services.

2.2.2 Design approach

(1) Design methodology

A number of decisions which affect the energy efficiency of buildings are made at an early stage of design. A specific methodology should be adopted which will identify significant factors and ensure that they are given attention at the proper states of design. The methodology should be incorporated into the timing and into the overall pattern of decision-making, where many factors have to be balanced against each other and integrated into a single design solution.

It may be possible to explore several different design possibilities during the course of the design process. But, the number and the extent of the studies will be limited because of the economics and time-constraints of the design process. It is, therefore, important to have a clear objective at the start of design. Initial design concepts inevitably precede analysis. If basic design concepts are not well-informed, then detailed design cannot produce the best results.

To ensure that the energy objectives have been established in the initial and detailed designs, BS8207 suggests that the following procedure should be adopted:

(a) The client's requirements should be established. It is especially important to gain a thorough understanding of the client's needs and their energy implications at an early design stage.

(b) The calculation method to be used in estimating energy requirement should be established, as explained in its Clause 4.

(c) Energy targets (Clause 5) should be established.

(d) A check-list should be used to ensure that significant points are not overlooked.

(e) Quantitative assessments of the energy requirement should be made periodically during the development of the design to assist decision making and to ensure that the design is on course for its energy objectives.

(f) Sufficient information should be included in contract documents to ensure that those using them can understand what is required.

(g) The estimated energy requirement and its economic implications should be reported at the presentation to the client of the scheme design and at the completion of the detailed design.

(2) Check-list and timing of decisions

The timing of decisions is important. The bar chart in Table 2.1 identifies some of the factors involved in designing a new building, and shows how early in the design process they may become fixed, i.e. typical decision timing, in relation to the stages of the RIBA *Plan of Work* stages.

When decisions are taken without consciously considering energy use implications, it is improbable that they will be the best possible. Check-lists help to ensure that significant points are not overlooked during the development of a project. BS8207 shows an example of an energy design check-list in its appendix B. It may be convenient to prepare subsidiary check-lists for particular aspects of design. These check-lists should be integrated into a certain framework. In this sense, a checklist for inter-disciplinary design working has been developed with particular reference to daylighting and lighting design aspects, and will be presented in a later chapter.

Table 2.1 Bar chart showing timing of design decisions (from Table 1 of BS8207)

Design decisions	'RIBA Plan of Work' stages*					
	Briefing		Sketch plans		Working drawings	
	A. Inception	B. Feasibility	C. Outline proposals	D. Scheme design	E. Detail design	F. Production information
1. Agree energy objectives and criteria	—					
2. Define uses, including changes of use, to be allowed for	—					
3. Identify use factors affecting zoning	—	—				
4. Select environmental standards	—	—				
5. Examine site suitability, restrictions, alternatives	—	—				
6. Consider building shape and its arrangement on the site		—	—			
7. Decide main methods of ventilation		—	—			
8. Plan building to facilitate zone control, heat reclaim and to minimize transmission losses		—	—			
9. Design fenestration taking account of lighting and internal requirements		—	—	—		
10. Select fuel(s) and provision to be made for alternatives		—	—			
11. Make space provisions for fuel change			—			
12. Choose basic building construction taking account of insulation and thermal response properties			—	—		
13. Provide for controllable ventilation				—	—	
14. Detail to minimize uncontrolled ventilation					—	—
15. Make main decisions about plant type, layout and controls strategy			—	—		
16. Decide on reclaim and non-depleting sources			—	—		
17. Develop plant design					—	—
18. Design artificial lighting and controls, taking account of daylight availability and lighting demand patterns				—	—	—
19. Determine measures to ensure efficient use of power (e.g. power factors, maximum demand control)					—	—
20. Prepare user manual incorporating energy aspects						—

*The stages are reproduced from the *RIBA Plan of Work*, published by RIBA Publications Ltd.

2.2.3 Energy implications of daylighting and artificial lighting

British Standard BS8206 *Lighting for Buildings*, Part 2 *Code of practice for daylighting*, refers to case studies with regard to energy efficiency in buildings [BS8206 Part 2, 1992, Clause 9.1]: "in RIBA case studies of buildings classified as 'energy efficient', it was found that in general the shallow plan, daylit, naturally ventilated buildings had around half of the primary energy consumption (in MJ/m^2) of deep plan, air-conditioned buildings with extensive artificial lighting. Another study by BRE (the Building Research Establishment) indicated potential energy savings averaging 20 % to 40 % in offices and factories if daylighting is used effectively."

In order to achieve such energy saving by promoting the use of daylight, there are two issues to consider, namely:

- the designers' attitude to exploiting daylight, and
- the building's overall energy balance, in terms of the integration of building functions.

(1) The designers' attitude to exploiting daylight

Within the UK, lighting accounts for around 5 % of the total primary energy consumed. However, in some types of building, such as office blocks, 30 % to 60 % of primary energy (a fair reflection of energy cost) is used by lighting [BS8206 Part 2, 1992; Littlefair, 1990]. In such buildings the exploitation of daylight, combined with appropriate control methods, can be an effective measure to reduce this energy cost, in terms of both replacing, or supplementing, artificial lighting and the use of solar energy gains.

The designer's attitude to exploiting daylight is an important factor to promote energy saving with daylighting. Cooper and Crisp [1984] identified, through a series of interviews with architects and engineers, that there were three separate groups amongst the designers according to their attitudes to the use of daylighting as a means of reducing fuel consumption when designing office accommodation:

(a) Designers who gave no explicit thought, or attached no importance, to the use of natural light as a criterion on which they should base their designs for fenestration and lighting.

(b) Designers who, although they considered or were aware of the possibility of using daylighting, rejected it as inappropriate for one reason or another, i.e. disadvantages or problems of daylight use.

(c) Designers who both considered using daylight and tried to use it;

While one group of designers exists who are predisposed towards exploiting daylighting, there are two other groups who are not. The reason why the designers of group (a) had not attempted to use natural light was due "to deficiencies in their colleagues or to demarcations between the respective areas of authority, responsibility, competence, or specialist skills of members of their design team". (Whether their building may be daylit or not depends on the consequences of other decisions they made during the course of design.) The reasons why the group (b) did not exploit daylight involved its disadvantages or problems the designers associate with its use, e.g. *variety of its intensity*. Some of these problems which these designers pointed out, however, were regarded as limited and soluble by those who are keen on exploiting daylight. Cooper and Crisp suggest that designers' decisions about whether they will exploit daylighting needed to be viewed as choices that many be as influenced by their own quite specific preferences, prejudices and beliefs as they are by any concrete demands imposed by the obdurate nature of reality [Cooper and Crisp, 1984].

In this sense, simple provision of information and design aids will, of themselves, make little impact on the design practices of these two groups. In order to promote the exploitation of daylight, Cooper and Crisp suggest that education and demonstration are necessary to overcome the following countervailing tendencies:

(i) Lack of consideration: the neglect or indifference shown to the use of daylight by some designers; and

(ii) Lack of credence, and outright hostility, towards the usability of daylight.

For those who are predisposed towards exploiting daylighting in their designs, meanwhile, the approaches proposed by Cooper and Crisp involve: in-service training programmes, including provision of guidance about where, when and under what circumstances daylighting can usefully be exploited in the design of a new buildings; demonstration of working practices, particularly those involving co-operation between architects and engineers. In this sense, it would be advantageous to develop a framework for the design process in terms of inter-disciplinary working.

(2) Overall energy balance in relation to artificial lighting installation

While energy consumption of the lighting installation is of concern to the lighting designer, the building designer or his specialist advisor is concerned with the overall energy balance of the building. To assess this, he has to examine the interaction between the pattern of building use, the building structure, the natural lighting, the artificial lighting, and the heating, cooling and ventilating system. Ideally, none of these aspects should be considered in isolation [BS8206 Part 1, 1985: Clause 6]. In the design of windows, for example, daylight is only one of several factors to be considered. Windows can affect the energy balance of the building by increasing both conduction heat loss and solar gain, and to a lesser extent, infiltration losses [BS8206 Part 2, 1992: Clause 9.2]. Shallow daylit rooms facing a south direction whose windows must be permanently closed may need air conditioning to establish comfortable conditions in summer. Under these circumstances deeper, artificially lit and mechanically ventilated interiors with windows serving primarily as view apertures may offer a better solution for plan arrangement, internal environment and energy demand [CIBSE Application Manual *Window Design*, 1987, Section A1.2.5]. In order to achieve energy savings in a building, meanwhile, not only should daylight be admitted to the building but artificial lighting installation with suitable controls needs to be developed to ensure the displacement of energy used for electric lighting [BS8206 Part 2, 1992]. Lighting design should be carefully carried out so that desired lighting conditions are provided at minimum energy cost. It should also be borne in mind that an installation can be expensive in terms of first cost and running costs. There are two factors which control the energy consumption of an artificial lighting installation, i.e. the power required to provide the lighting and the time for which that power is used. These issues are described in Appendix B.4.

2.3 Case study

2.3.1 Background of the case study

To study an energy-efficient building design practice based upon the RIBA *Plan of Work* and BS8207 "*Energy Efficiency in Buildings*", a case study was carried out. This case study involved observing a small group of designers who were working through the strategic phase in a low-energy design project, undertaken as a part of the MSc course in *Energy and Built Environment*, at Cranfield Institute of Technology between January and March 1992. British Standard BS8207 was used both to structure the plan of work and as a checklist. The outcome was the development of a workable building model which the group felt complied with the brief. The case study is described in detail in Appendix C of this thesis.

2.3.2 Findings from the case study

The result of the case study can be summarised as follows.

The design process was undertaken using many iterative steps allowing ideas to be explored in numerous directions. During the course of the design process, the members of design group observed were found to be very good at communicating with each other in a sense that they develop a design working as a team. Their working practice could be characterised as follows:

(a) Common understanding of a brief

The design group held a series of intensive meetings at the beginning of the project, where the members analyzed the brief and developed their design objectives. This suggests that these meetings in which every member of the design group took part allowed to the members to share a common understanding of the brief and design philosophy as well as design objectives.

(b) Individual role play

During the course of the design development, each member of the group was in charge of his own duty, e.g. thermal simulation and daylighting design, using such tools as *TAS*, a thermal analysis system, the *Daylight Program* for daylighting design, and Philips' *Calculux* for designing artificial lighting installations. In other words, the design group established the roles clearly which each member has to play. It was found that this allowed the members of the group to carry out their own duties individually, with reasonable competence, and, eventually, helped the group work efficiently.

(c) Frequent communication

The design group also had frequent meetings throughout the project period in order to organise the individual members' works into a total design solution and conduct their design process. It was found that such meetings allowed important design decisions, e.g. the building form and construction type, to be made by the design group as a whole, rather than one individual member, while alternative design solutions could have been developed by one or a few members.

At the end of the group project, the design which this design group finally presented received the top mark of that year. This case study may suggest that the following issues are some of the keys to a successful design working practice:

(a) Every designer involved in a design project should have a good, common understanding about the brief as well as the design objectives and approach. This could be achieved by involving all members of the design team in the briefing stage.

(b) Whilst each individual designer works with his/her discipline on the basis of the common understanding, all members of the design team should have opportunities to take part in the development of the design by communicating with the others. In this sense, having such meetings at pertinent stages is vital to achieve a quality-assured design within a limited period of time.

Chapter 3

Chapter 3
A CONCEPTUAL MODEL OF DESIGN ACTIVITIES

The purpose of this chapter is to provide a basic discussion on conceptual models of the design process which will be the basis of a framework for inter-disciplinary building design working developed in a later chapter. In Section 3.1, various views to design methodology among different disciplines are considered. In Section 3.2, the design process is discussed in terms of its logical sense, and then the derivation of an initial proposal and the development of a design solution are considered taking account of the use of a stereotype as a starting point. In Section 3.3, in order to formalise design activities, particularly the development of a design solution, two kinds of design variables, i.e. *design decision variables* and *performance variables* are introduced, and design is considered to imply 'mapping' between the description of an artefact and its performance characteristics. Then, the role of information within a design process is considered, and, eventually, a "three-space" conceptual model of the design activities is proposed. Finally, in Section 3.4, it is argued that such a mapping could be represented using ‘knowledge’.

3.1 Introduction: Approaches to a Rational Description of a Design Process

It is thought that the building design process needs to be described rationally in order to develop a framework for inter-disciplinary working. The study of design methodology to rationalise and formalise a design process dates back to the early '60s, when serious attempts were made to improve the results of design by establishing certain procedures or methods to follow [Mackinder and Marvin, 1982]. As mentioned in Section 1.2, design encompasses numerous disciplines. Because of the diversity of approaches that may be taken, design can be described in many different ways, and various models of design, which are considered as limited abstractions of particular phenomena, have been proposed through case studies and theoretical accounts.

Lloyd and Scott argue that there are three distinct disciplines for design study, i.e. architecture, engineering or industrial design, and computer program design [Lloyd and Scott, 1994 and 1995]. They point out a coherent model of design process evolved in each of these disciplines which can be characterised in relation to the education provided in each area, as follows [Lloyd and Scott, 1995]:

(a) The 'formal' design process of architects

"Architects receive a project-based education exploring architecture through specific design projects of certain types of building. This approach puts an emphasis on design solutions. The design problem is perceived only in reference to the general form of solution."

(b) The representational design process of engineers

"Engineers are provided with an analytical education; an education that concentrates more on abstract principles ... than on specific design project experience. Perhaps it is this that has led to models of the engineering design process which are concerned with problem analysis before solution synthesis."

(c) The structured design process of computer programmers

"A computer programming education sits somewhere between engineering and architecture in terms of the amount of abstract principles of programming and the amount of direct project experience. Models of computer program design concentrate on the structure of problems and how designers negotiate between

> problems and solutions, and sub-problems and solutions. The essence of this that design problems have a structure of sub-problems which can be broken down, solved independently, and recompiled to produce a complete solution."

Lloyd and Scott continue: "every design problem, regardless of discipline, could easily have all three concepts associated with it. ... If we consider one specific design problem in any discipline we are likely to find aspects of representation, form, and structure within the confines of that problem. Further, individual designers will apportion different weights to each concept depending on their education and experience [Lloyd and Scott, 1995]."

This comment suggests that these concepts, particularly those associated with architects and engineers, need to be taken into account to develop a framework for inter-disciplinary building design working, that involves professionals from architecture as well as engineering. It may not, however, be easy to derive a rational description of the building design process which would be satisfactory in terms of both architecture and engineering. But, it is surely challenging to develop such a rational description that takes account of such diverse concepts between the disciplines involved in the building design process, rather than any particular one of them.

In Section 3.2 a design process is discussed in logical terms with regard to form and representation, referring to two essays by March and Hawkes. Particularly, the formal design process is considered in terms of the use of *stereotype* by referring to Hawkes's paper. In Section 3.3, a conceptual model, or a rational description of the design process is proposed which describes the development of a design solution while taking account of the use of stereotype. Then, Section 3.4 concerns the designer's knowledge or expertise with regard to stereotype and the development of a design solution.

3.2 Rational Description of a Design Process

3.2.1 The three-phase model

Various models of design, which are considered as limited abstractions of particular phenomena, have been proposed through case studies and theoretical accounts. Among them, there is general agreement on the three-phase design model. This model consists of the three phases: 'analysis', 'synthesis', and 'evaluation', as shown Figure 3.1 [Oxman and Gero, 1987; Coyne et al., 1989].

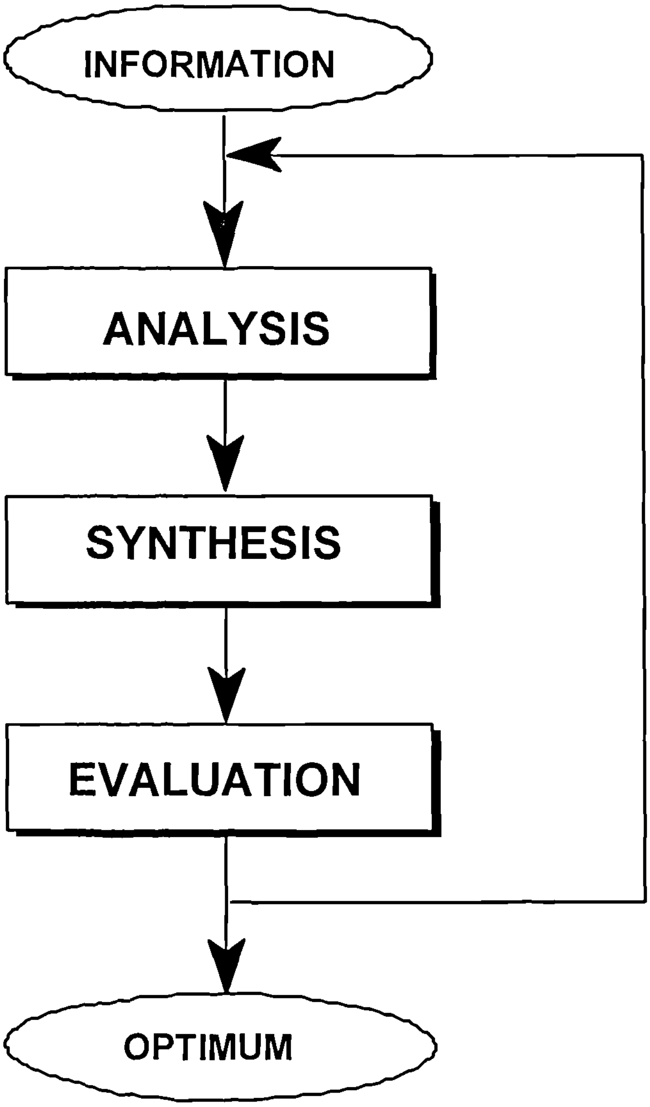


Figure 3.1 Three-phase model of design

The first task is to diagnose relevant information and define a design problem: i.e. to recognise the desire, or dissatisfaction, and produce an explicit statement of goals. The second task involves finding plausible solutions. The third task concerns judging the validity of the solutions relative to the goals and selecting from among alternatives. The results of the evaluation may be fed back to the analysis phase to be re-analysed. This return loop from the 'evaluation' to the 'analysis' phase describes a back-tracking in which the proposed solution is revised and improved by re-examining the information, including the result of the preceding evaluation phase, and may be re-iterated until a satisfactory solution is obtained. These three phases therefore form the basis of a framework for planning, organising and evolving design projects.

The important properties of this 'three-phase' model are:

(i) the process is sequential in that evaluation follows synthesis, which is preceded by analysis; and

(ii) it is cyclical in the sense that the sequence may be repeated many times: evaluation results in a revised analysis of the problem, which leads to the synthesis of a new provisional solution. Through such a cyclical process more information is accumulated to improve the solution during the development of a design, and each cycle is progressively less general and more detailed than the preceding one.

This three-phase model assumes that design activities can be rationalised in such a way that a designer works only on the information given or available to him/her, and ignores the possibility of 'intuition' or 'creative leap', which is often a feature of design.

3.2.2 Logic of design and the PDI-model

(1) Three modes of reasoning

There are three distinctive modes of plausible reasoning proposed by C S Peirce [March 1974]. They are called *deduction*, *induction* and *abduction*, as shown in Table 3.1. The three modes of reasoning are themselves derived from permutations of three types of information, namely the data describing a '*case*' of interest, general '*laws*' and the '*result*' of applying the *laws* to the *case*. Here, '*deduction*' is the process by which a '*result*' is derived from a '*case*' and '*laws*' (Table 3.1 (a)); '*induction*' is the process by which a general '*law*' is produced from the other two kinds of information (Table 3.1 (b)); and '*abduction*', or '*production*', infers a '*case*' from a '*result*' and the '*laws*' (Table 3.1 (c)). Abductive reasoning, in other words, takes place where we find some curious circumstance, which would be explained by the supposition that it was a case of a general rule, and thereupon adopt that supposition.

Table 3.1 Three modes of inference in a logical context

Logical context	Known		Unknown
(a) Deduction	Case	Laws	Result
(b) Induction	Case	Result	Law
(c) Abduction / Production	Result	Laws	Case

(2) Synthetic reasoning and the PDI-model

March uses the three modes of reasoning analogously for his model of inference in design, while taking account of an analogy with empirical science. In his essay *The logic of design and the question of value*, March introduces three terms for the purpose of developing a design theory as follows:

- '*decomposition*' for the outcome of deductive reasoning,
- '*supposition*' for the outcome of inductive reasoning; and
- '*design*', or '*composition*' for the outcome of productive reasoning.

Here, *decomposition* comprises the characteristics of a design that emerge from analysis of the whole design, or composition. *Supposition* forms a working rule of some generality, i.e. a hypothesis in scientific sense. According to March, a *supposition*, more loosely, is an idea, a theory, or in modern usage a model, a type.

Table 3.2 Three modes of inference in a design context

Design context	Known		Unknown
(a) Deduction	Design	Rules	Performance / decomposition
(b) Induction	Design	Performance	Rules / supposition
(c) Abduction / Production	Performance	Rules	Design / composition

These terms are presented in relation to the three modes of reasoning in Table 3.2. Then, March discusses his model of inference in design in logical terms, while taking account of an analogy with empirical science.

According to March, we naturally conceive of science as having three tasks:

(i) discovery of laws, accomplished by inductive reasoning;
(ii) discovery of causes, accomplished by hypothetical, or abductive reasoning; and
(iii) prediction of effects, accomplished by deduction.

Then March quotes Peirce's remarks: "We conceive of rational designing as having three tasks:

(i) the creation of a novel composition, which is accomplished by productive reasoning;
(ii) the prediction of performance characteristics, which is accomplished by deduction; and
(iii) the accumulation of habitual notions and established values, an evolving typology, which is accomplished by induction."

Here, it is important to make distinction between logic, empirical science and design. Logic is concerned with abstract forms; science investigates extant forms; and design initiates novel forms. A logical proposition is not to be mistaken for a design proposal; a scientific hypothesis is not the same thing as a design hypothesis. Here, an hypothesis in science is a general principle induced from particular events and observations, whereas one in design is a particular instance produced from general notion and specific data [March, 1994].

Importantly, having considered the analogy between logic, empirical science and design, March argues that the chief mode of reasoning of design as well as science is inductive, i.e. 'synthetic' rather than 'analytic'. This idea leads to the 'production-deduction-induction (PDI)' model of design, where a rational design proceeds in this fashion [March, 1974]:

(i) From a preliminary statement of required characteristics and a presupposition (pre-working rules), or protomodel, the first design proposal is produced or described.
(ii) From design suppositions (working rules) and theory, and the first design proposal, the expected performance characteristics may be stated or predicted.
(iii) From the performance characteristics and the first design proposals, other design possibilities, or suppositions (working rules) are induced or evaluated.

The cycle then begins again:

(i) From a revised statement of characteristics and further, or refined, suppositions, a modified design proposal is produced, and so on.

The PDI model assumes that:

(a) certain characteristics are sought in a design to provide desired services;
(b) a design proposal is put forward on the basis of previous knowledge and some general presuppositions.

The PDI-model implies linearity in the design process, one mode of reasoning following another in the convergence to a "best fit" solution. This model also represents design as an iterative process, where the three modes of reasoning are associated with design activities as follows:

(i) Abduction / Production creates: abductive reasoning can only be inferred conditionally upon our state of knowledge and available evidence.

(ii) Deduction predicts: deductive methods can then be used to predict measures of expected performance by the application of further models and theories to the particular design proposal. (The mode of prediction is essentially deductive.) Deductive inference is determinate, although probabilistic.

(iii) Induction evaluates: the design and its expected characteristics are used to infer new generalisations and supposition (working rules).

This model cannot explain where a design solution comes from, but assumes a design proposal at the beginning of the design process. But, the PDI-model seems to illustrate a cyclic learning process in which suppositions or working rules are obtained. It is important to notice that inductive reasoning is used to evaluate the presupposition upon which the design proposal was obtained and developed, rather than the design proposal itself, and can lead to a new working rule. In other words, induction criticises the original presuppositions in the predictive phase, and provides more discriminating models for the next round of the cycle. As a result, changes might be made to the designers' system of values, or working rules, during the design experience in regard to hypothesis, information, decisions, outcomes and utilities. In short, such an iterative procedure represents how designers learn, or improve, their working rules, instead of developing a design solution.

3.2.3 Architectural design and stereotypes

It is interesting that a designer could derive a design, i.e. a set of descriptions of an artefact, when some performance requirements are given and the rules are known. Assuming that designers ideally have knowledge of all sorts of predictive *laws* (rules), then once they know what kinds of performances the designed artefact has to achieve, what they have to do is to reverse the *deduction* process, i.e. to derive a set of descriptions of the artefact (a *case*) from its expected performances (a *result*) using the predictive *laws* (Table 3.2 (c)). This is entirely analogous to an '*abductive / productive*' process.

The reality of architectural design is, however, so complex that design activities cannot be explained in such a logical and over-simplified manner. Both the three-phase model and the PDI-model are rational descriptions which assume that design is a process which progresses through iterative procedures. Yet they may have some possible deficiencies in the architectural design context, because they assume that the first hypothesis, or a probable solution, is arrived at by rational analysis of the problem in all its respects.

In the three-phase model as well as the PDI-model, it is considered that designers do not usually start with a description of an artefact, but with some idea about its desired performance, which normally appears in a design specification or brief, and then they endeavour to arrive at a description of the artefact. The process of obtaining a description of the artefact, or a 'hypothesis', is understood as a particular instance produced from a general notion and specific data, i.e. composition. It is the outcome of abductive/productive reasoning in the PDI-model. This can be seen as a 'representation-based' view, which is considered to describe an engineering design, as Lloyd and Scott explained (see Section 3.1). Considering the differences which exist between engineering and architectural fields with regard to how the initial hypothesis is arrived at, then a rational description of the building design process should reflect such a differences.

In an essay, '*Type, Norms and Habit in Environmental Design*', D. Hawkes argues that the starting point for most building is a stereotype solution [Hawkes, 1974]. He describes the term 'stereotype' as follows:

> "it is simply that there is, at any point in time, a generally held notion about the nature of a good solution to any recurrent building design problem and that it is this notion which frequently inspires the initial design hypothesis."

According to Hawkes, the stereotype, because of its looseness, does not intimidate the designer, but gives him/her a starting point and permits, even invites, further development and exploration in the design process [Hawkes, 1974]. This may be understood that most architects are capable of obtaining the first hypothesis (possible solution) at the beginning of the architectural design process with little analytical process other than studying information such as their clients' requirements. It is understood that designers, or architects in this context, have stereotypes as a part of their expertise, and such stereotypes may be considered as obtained through their education and training,. In other words, this is a characteristics of architectural education, as classified by Lloyd and Scott [1995].

One may have a question regarding such a stereotype-approach: the creativity of the design based upon such a stereotype. March suggests that there is a tendency for the current stereotype, or general notion, to become too highly specialised so that its progressive evolution is jeopardised [March, 1974]. Hawkes, however, claims that "it can - and frequently does - play a *creative* role by allowing the designer to begin the cycle of analysis and revision from a reasonably confident position [Hawkes, 1974]." In this sense, design initiation is understood in terms of a hypothesis which is more or less chosen, rather than created, by the architects. It is based upon their experience and expertise, and then developed, or improved through the design process which contains analysis and evaluation.

Meanwhile, Hawkes shows how a new design habit becomes established and comes to dominate previous notions with respect to the design of the modern office building.

He describes how office-building design since the nineteenth century has evolved through a series of distinct 'stereotypes' that are redefined as priorities and technology development change [Hawkes, 1974].

> "The answer appears to lie in the realisation that the current stereotype does not supersede all others. There is, in fact, a store of accumulated experience which contains all previous solutions and which will be enlarged in the future with the addition of new examples inspired by changing building technology, organisational ideas and physical, social and cultural environments. This view demands a return to earlier stereotypes to see what they might offer when modified to exploit developments in technology which have occurred since their days. A healthy situation would be one in which solutions with a high dependence on technology could co-exist with others which achieved their goals by simple means."

In short, such a stereotype does not remain the same, but evolves depending upon social and technological circumstances. The survival of stereotypes in the past has been a matter of trial and error in practice: the fittest have survived as evidence of their utility. Such evidence is usually modified by a designer's judgement, developed from his experience, and in time becoming part of his intuitive response.

How are such judgements made? If they are the result of internalised personal judgement, experience and intuition alone, then the three modes of the PDI-model become inextricably entangled and no powerfully sustained use of collective, scientific knowledge is possible. Design will remain more or less personalistic and a matter of opinion. If the design process is externalised and made public, as it evidently must be, for team work to be fully effective, then the three stages of the PDI-model are worth making explicit so that as much available knowledge as seems appropriate can be brought to bear on the problem. With regard to inter-disciplinary design working, the judgement should be, and needs to be externalised. In this sense there seems to be a close connection between such evolution of stereotypes and the learning process represented by inductive reasoning in the PDI-model.

3.3 Three-Space Conceptual Model of Design Activities

Having discussed the design activities in terms of logic and stereotypes, it is understood that a building design process involves:

(1) obtaining a hypothesis (an initial proposal) based upon a stereotype, and formed through the designer's experience, and

(2) the development of the design solution: the hypothesis is developed through the design process which involves further analysis and evaluation.

The following discussion concerns the derivation of a hypothesis from a stereotype and the development of a design solution through a design process.

3.3.1 An initial proposal and the use of stereotype

Having introduced the concept of 'stereotype', it can be considered that architects have the basis for proposing an initial solution as a part of their expertise, so that they are capable of forming their design hypotheses very rapidly. In other words, in most, if not all, design processes, such a basis of a design solution readily exists, rather than having to be created through some logical process.

This suggests that a designer's specialist knowledge, or expertise, that enables him/her to respond to a problem statement (performance requirements to be attained) and come up with a solution, seems to contain a considerable number of the predictive *laws*. This seems to reflect the fact that generally the more experienced the designer is the more effectively he/she can derive possible design solutions from a set of performance requirements. However, such a process requires that the predictive *laws* are adequate to the task, particularly where demands are made for the use of unfamiliar materials or concepts.

While being heavily influenced by the architect's knowledge of stereotype, the activity of obtaining an initial proposal should be carried out taking account of information such as the client's requirements, site constraints, technological development, social trends and so on. Looking at the Royal Institute of British Architects, RIBA, *Plan of Work*, for example, most of such activities should take place within the first stage, i.e. '*Inception*'. An initial proposal for the building form and window design for example, should be influenced by information such as the client's requirements and site conditions.

To develop a proposal based on a stereotype, it is essential to obtain information concerning, for example, the purpose of the building, the activities carried out within the building and site conditions such as other buildings around the site. This suggest that an analysis phase does exist, where such information is studied in order to derive an adequate hypothesis from stereotypes.

3.3.2 *Design decision* and *performance variables*

In Chapter one, three features of the design activity were presented:

(i) a *purposeful* activity, which involves a conscious effort to originate a system, or an artefact, in order to attain a certain desired state of performance;

(ii) a *goal-directed* activity, during which design decisions are made in order to produce a set of descriptions of the artefact which satisfies a set of performance requirements and constraints; and

(iii) an *ill-defined* activity, which has no straightforward process to follow to make decisions.

Table 3.3 Design parameters: *design decisions* and *performance*

Design decisions	- floor area - glazed area - lighting system etc.
Performance	- lighting level - temperature - cost etc.

Considering the first two features in particular, design seems to involve two kinds of parameters: '*design decisions*', which describe collectively the artefact to be designed, and '*performance*' representing the desired performance of the designed artefacts, or, simply, the designs (Table 3.3).

In order to express these parameters, two kinds of *design variables*, i.e. '*design decision variables*' and '*performance variables*', respectively, could be introduced. It is considered that once an initial design proposal has been obtained, it is developed into a design solution. The development of a design solution is thought to involve making decisions to these *design decision variables* as examining its resulting performance in terms of the desired qualities.

Coyne et al. [1989] illustrated the relationship between design descriptions (decisions) and performances (Figure 3.2). Since a design activity is goal-directed, a designer has to have a design *goal*, or goals, prior to starting a design process ('acquisition of a *goal*'). The design goal can be interpreted into '*design objectives*' which must be satisfied for the design goal to be met ('establishing design objectives'). In order to attain these objectives, the *performance variables* must acquire adequate values within certain ranges. These ranges may be called '*design criteria*'. During the course of the design process, the designer assigns values to the *design decision variables*, which describe the artefact being designed. Importantly, by making decisions about the values of these *design decision variables*, the designer can control the values of the *performance variables* so as to achieve the *design objectives*, and, eventually, the design *goal*.

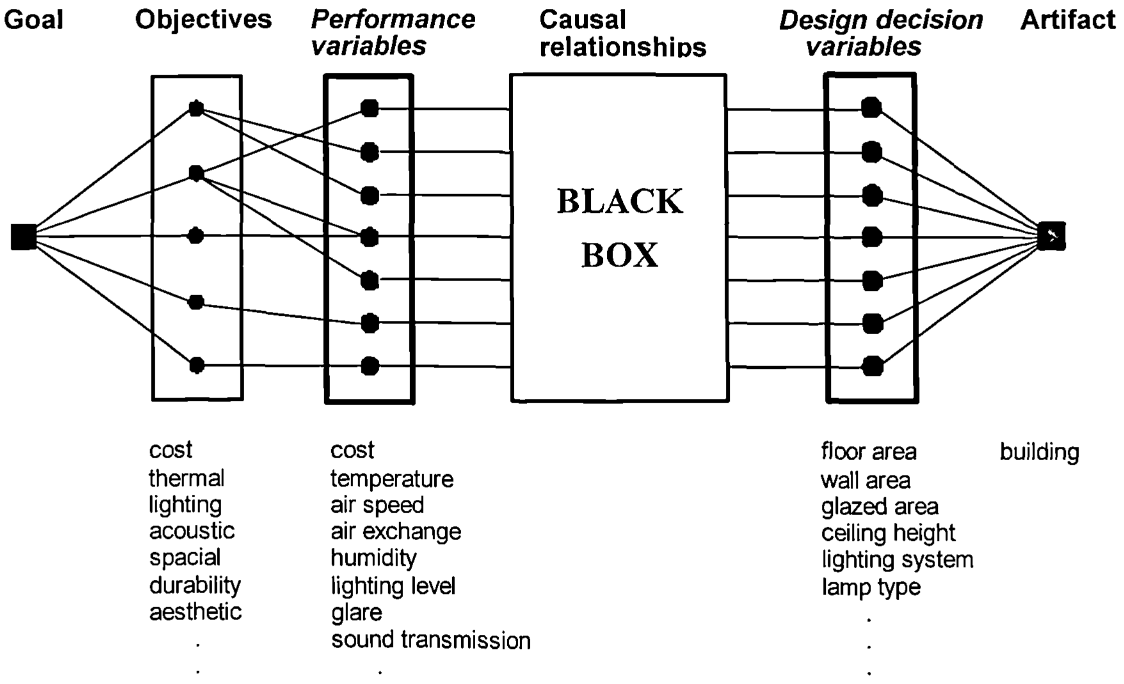


Figure 3.2 The relationships between a goal, objectives, *performance variables*, and *design decision variables* (Reproduced from *Knowledge-Based Design Systems*, [Coyne et al.,1989]).

3.3.3 The mapping between the *design decision* and *performance spaces*

The '*design decision variables*' describing the artefact and the '*performance variables*' representing the performance characteristics of the artefact, are thought conceptually to form two spaces. Let us call these spaces '*design decision space*' and '*performance space*', respectively. The artefact to be designed can be described within the *design decision space.* A stereotypical solution, i.e. an initial proposal, is considered to be described in the *decision space.* The anticipated performance characteristics of the solution will be expressed within the *performance space.* The desired performance characteristics can also be described in the *performance space.*

Considering the discussion in Section 3.2, it can be recognised that the development of a design solution involves:

(a) making an effort to draw a certain description of the artefact to be designed based upon a stereotypical solution, so that a set of requirements concerning its performance are satisfied, and

(b) anticipating the performance of the artefact based on its description.

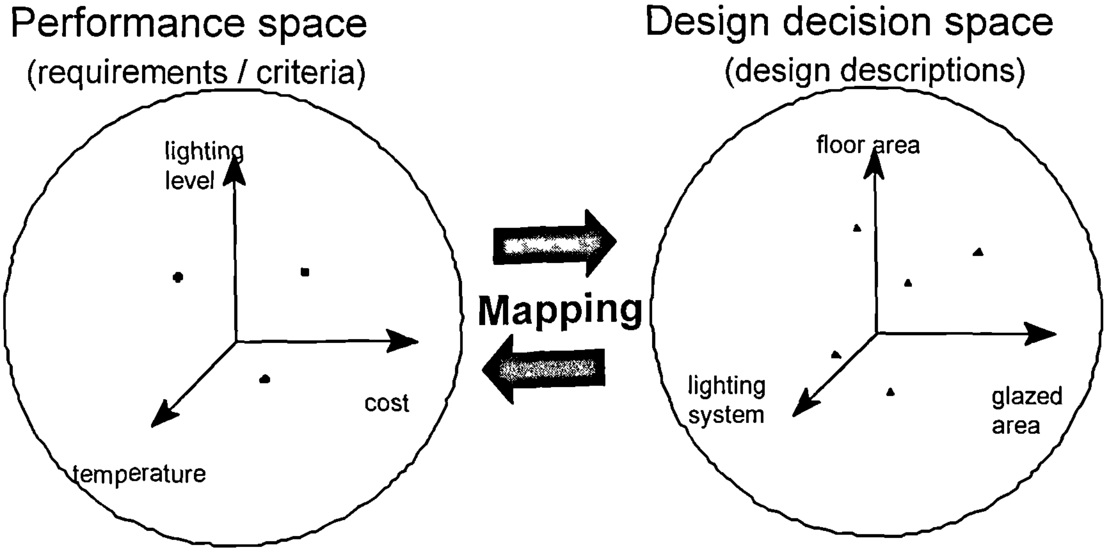


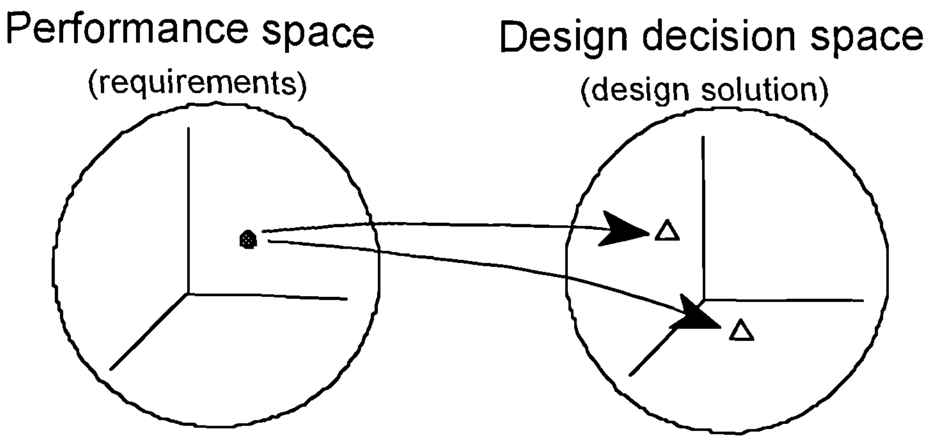
Figure 3.3 Design activities implying the mapping between the *performance space* and *design decision space.*

The ultimate purpose of the design activities is to obtain such values of the *design decision variables* that the *performance variables* will eventually have their values within a set of desired *design criteria.* In terms of the mapping between *design decisions* and *performance*, design activities could be undertaken in two directions: from the *performance space* to the *design decision space*, and vice versa. When a certain set of *design objectives*, or *performance requirements*, has been set up, a designer may be able to derive an initial proposal from them based upon his/her stereotype. Having established such initial values of the *design decision variables*, the designer may try to improve them so that the values of the *design decision variables* become appropriate, probably using his/her expertise. Consequently, the design activities to develop a solution imply the '*mapping*' between the two spaces (Figure 3.3).

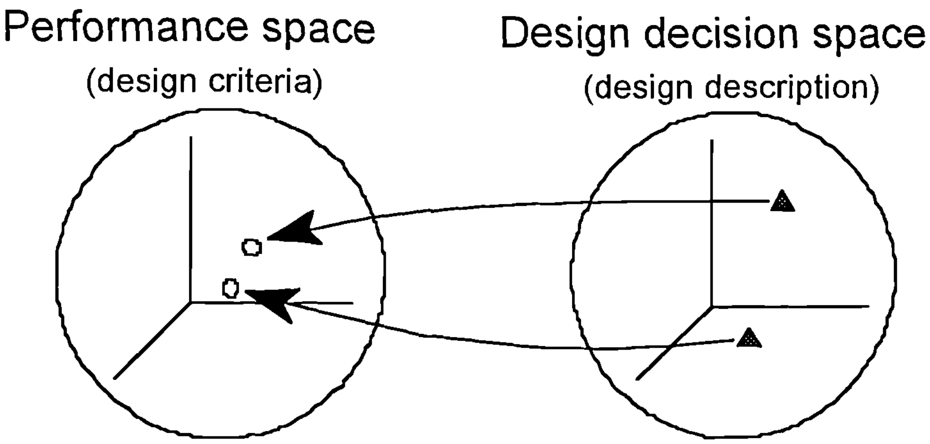
The modification of a design proposal could be perceived as the *mapping* of a certain set of performance requirements onto the design decision space (Figure 3.4 (a)). During the course of the design process, the designer also examines whether or not a certain design, i.e. a description of an artefact formed by a set of values assigned to these *design decision variables*, satisfies the set of *design criteria.* Such an operation involves predicting the performance of the artefact being designed and the evaluation of a design proposal. If the result proves unsatisfactory, he/she will have to seek another set of design decision values, and this activity will continue until the performance criteria are fulfilled. This 'performance prediction', or 'interpretation of a design', can be seen as *mapping* of the design from the design decision space to the performance space (Figure 3.4 (b)).

Such a process may also be explained in logical terms as follows. This is that a design is something in the real world about which logical *deductions* can be made. A design is a set of descriptions of an artefact, which may consist of statements regarding the physical components of the artefact in terms of geometry and material attributes, for example. Here, the '*laws*' could mean the theories and rules that represent the relationships between design decisions and performances. In order to predict the performance of the design, the descriptions may have to be interpreted using an inference process, given an appropriate set of prediction *laws* (Table 3.2 (a)). Such an interpretation process to derive the performance (a *result*) from the descriptions of an artefact (a case) using the *laws*, can be seen as '*deduction*' in terms of logic. This stresses the analytical or evaluative aspects of the design process.

Considering actual design activities, however, they cannot be characterised by only one of these logical processes, but may involve the '*deductive*', '*inductive*' and '*abductive / productive*' processes. Having synthesised a design proposal using a stereotype, the design team may then adjust the design solution to meet more specifically particular requirements (*abduction / production*). This is achieved through a process which evaluates aspects of the design solution in terms of desired performance characteristics (*deduction*). Then, the designer / design team may proceed via either '*deductive*' or '*abductive / productive*' processes to achieve a 'final description' of the artefact. The mapping can, therefore, be seen as a key to the development of a structure which allows a flexibility regarding the "starting condition" and the logical process involved in achieving the "final description" of the artefact.



(a) Derivation of a design solution



(b) Performance prediction

Figure 3.4 Two kinds of mapping between *design decision* and *performance spaces*

(a) Modification of a design solution:
mapping from the *performance space* to the *design decision space*;

(b) Performance prediction:
mapping from the *design decision space* to the *performance space*.

It has been stated that the design activities imply the *mapping from the performance space to the design decision space* representing the derivation of a design solution from given design requirements (see Figure 3.4 (a)), and *mapping from the design decision space to the performance space* suggesting prediction of the performance of the design and, eventually, its evaluation (see Figure 3.4 (b)).

Consequently the *mapping from the performance space to the design decision space*, conforms with the derivation of a design solution and modification, and the *mapping from the design decision space to the performance space* (that of performance prediction) corresponds to the '*evaluation*' (Figure 3.5).

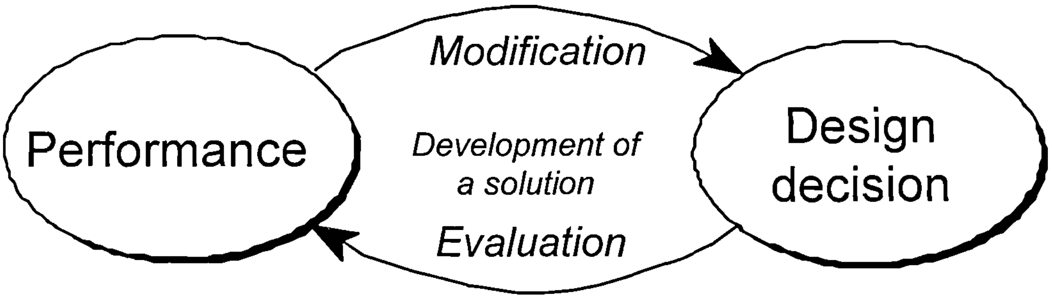


Figure 3.5 The mapping between ' *design decision*' and ' *performance*' spaces:

3.3.4 The three-space model and the design activities

Examining the Royal Institute of British Architects, RIBA, *Plan of Work*, most activities within an '*analysis*' phase of a process model appear during the first two stages, i.e. '*Inception*' and '*Feasibility*'. During these stages, while briefing is carried out, performance requirements and design criteria are established. At the same time, constraints have to be identified in terms of physical, technological, financial and legal aspects. What is demanded for these activities is deemed to be '*information*'. It is, in other words, essential to obtain information concerning, for example, the purpose of the building, the activities carried out within the building and site conditions such as other buildings around the site, in order to establish viable design objectives. It is at this point that stereotypes can be examined as a response to client's demands. Acquiring information and setting design criteria and constraints is considered to be one of the most crucial activities to develop a successful design.

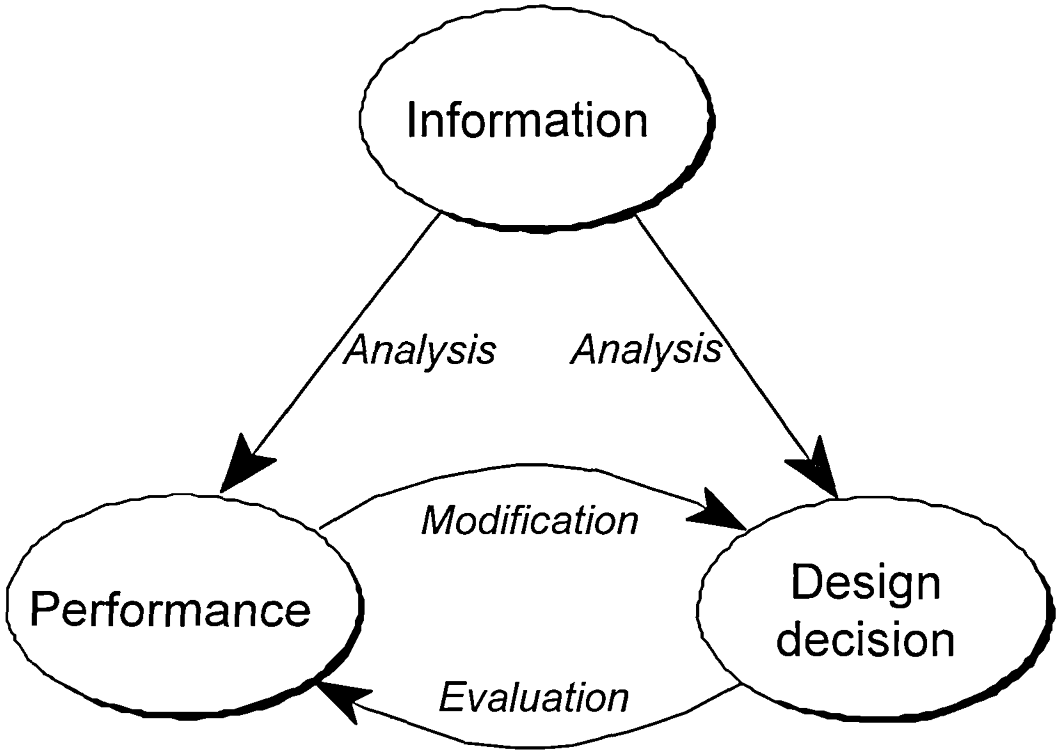


Figure 3.6 Three-space conceptual model of design activities, consisting of '*information*', '*design decision*' and '*performance*' spaces, and mapping between them.

For further development of the conceptual model which can represent the design activities involved in the design process, therefore, '*information*' should be a parameter of the design activities, together with *design decision* and *performance*. As a result, the third category of design variables associated with it, called '*information variables*', should be introduced, and a set of *information variables* will form an additional space, an '*information space*'. Here, in the case of the building design process, the *information variables* may represent facts and data acquired from clients, information regarding possible sites and the requirements of legal regulations. Consequently, a conceptual model can be developed which consist of three spaces, i.e. '*information*', '*performance*' and '*design decision*' spaces, and the design activities could eventually be described as *mapping* between them (Figure 3.6).

This three-space, '*information-design decision-performance*' model, illustrated in Figure 3.6, embodies the design activities as follows:

(a) The mapping from *information* to *performance* space represents establishing performance requirements or rules and design criteria within the performance space, based on information such as client's brief and environmental regulations (Figure 3.7 (a)). An example of a performance requirement or design criterion could be that 'the lighting level required within an area which in turn depends on the visual tasks that will be carried out within it.'

(b) The mapping from *information* to *design decision* space implies the derivation of an initial design proposal probably based upon a stereotype while taking account of identifying physical, technological and legal constraints. These physical constraints have consequences on the decisions about the shape of the building and its arrangement on the site. Mapping of this type may also involve supplying product information, e.g. data about various lamps, when design decisions, such as choice of a lamp type, are made.

(c) As explained earlier, the mapping from *performance* to *design decision* space means the derivation of a design solution taking account of performance requirements and criteria, and improving the design solution (Figure 3.7 (c)). It may also include the feedback of the evaluation results about previously proposed design solutions.

(d) The mapping from *design decision* to *performance* represents predicting the performance of a proposed design solution as well as its evaluation (Figure 3.7 (d)).

(e) Furthermore, there seems to be another mapping from the *design decision* space onto itself (Figure 3.7 (e)). This means that some design decisions are restricted by other previous decisions. For example, decisions on the area and position of windows may be hugely influenced by the orientation of the building.

This three-space conceptual model will be used as a basic framework to describe the building design process when a knowledge-based checklist tool for inter-disciplinary design working is developed. The development of the checklist, including the selection of design parameters as well as the identification of the relationships between these parameters, is discussed in the next chapter.

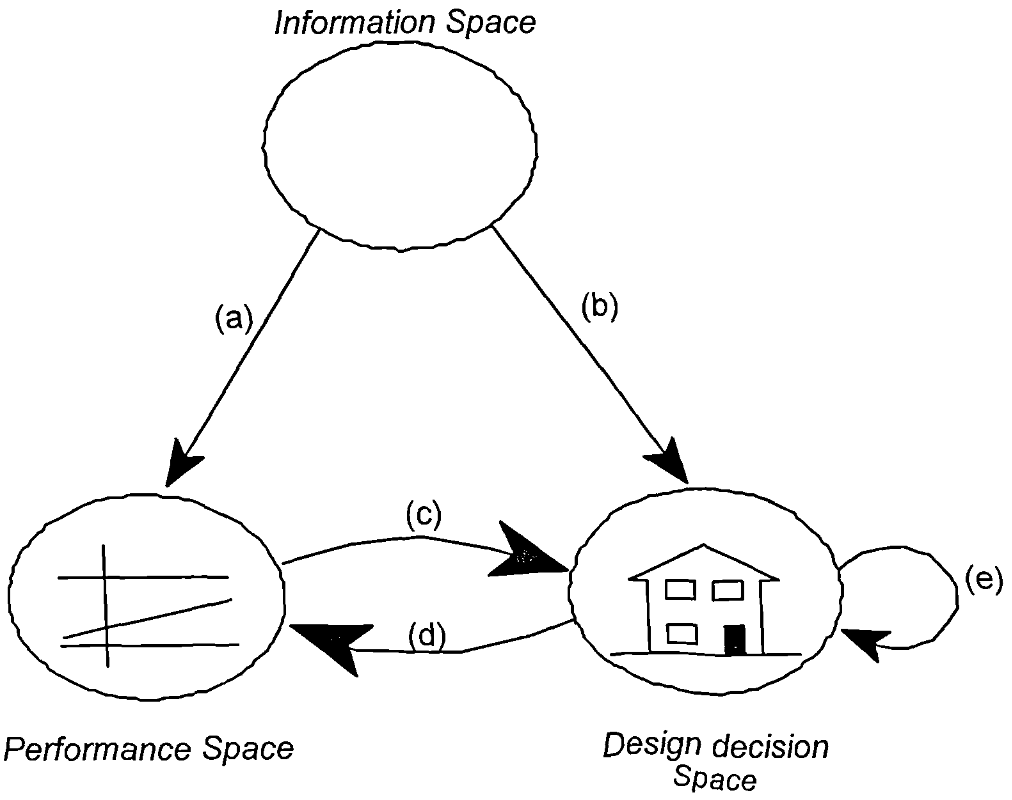


Figure 3.7 The mapping between the spaces [(a)-(e)], and design activities.

3.4 Mapping and Knowledge

3.4.1 Analogy with problem-solving

This section discusses the features of the design activities in relation to the knowledge required to pursue the design process. As discussed in Section 3.3.1, architects often use a stereotype in order to obtain an initial design proposal. The many previous attempts to formalise design methodology, particularly the development of a design solution, appear to involve a great deal of effort to constitute the mapping between *performance* and *design decision spaces.* It is interesting as an alternative to study design, by analogy, in terms of problem-solving.

Problem-solving is a process which implies searching for solutions. The search is concerned with exploring a state space which consists of possible states of a system. Some of these states may be restricted for some reasons. These restrictions are called *'constraints'.* Problem-solving is the process through which a solution is found, i.e. a state of the system which attains certain requirements, while exploring the state space taking account of the constraints. During the course of a problem-solving process, it is often necessary to search for partial solutions if the state space is very large. In this case, the transition of the system's state occurs within the state space as the search process progresses, and this transition of the state continues until a final solution state is reached (Figure 3.8).

It is evident that design generally involves some sort of search process in which designers tend to explore possible design solutions. Design could therefore be seen as problem-solving. In this case, considering the two spaces, i.e. *design decision* and *performance*, the space in which this exploration takes place is the *design decision space*, which is formed by *design decision variables*. Since design often is an ill-defined activity, which has no straightforward process to follow to arrive at a final design solution, designers seem to have to develop their ideas while exploring partial solutions as well as trying various alternatives. Looking at the three-phase, '*analysis-synthesis-evaluation*' model as well as the PDI-model of design, cycling through these phases appears to be the process of exploring the *design decision space* to find an appropriate design solution.

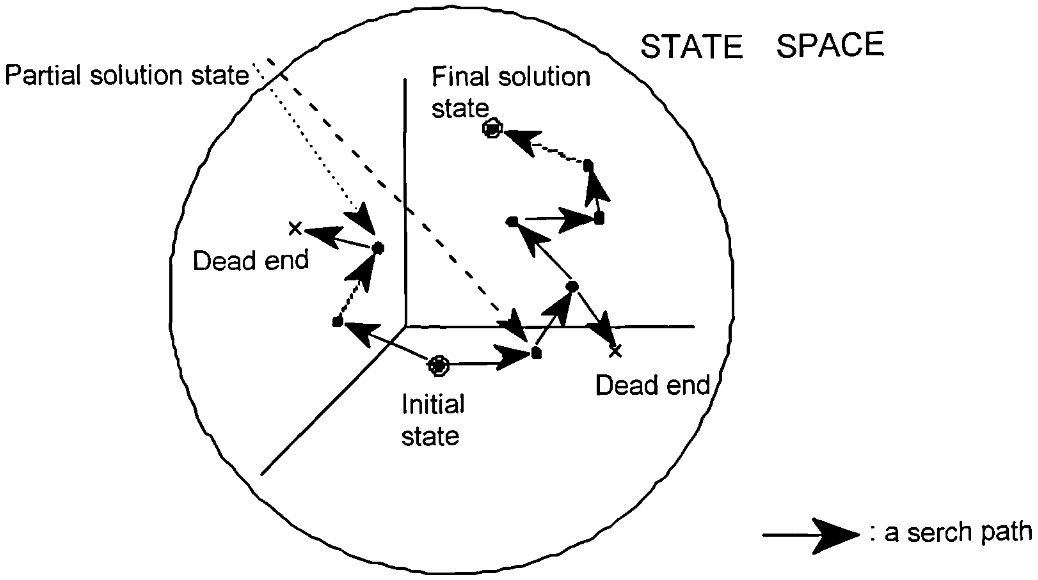


Figure 3.8 Search for a solution within a state space.

In order to make the search process efficient, certain search strategies, i.e. control mechanisms of the exploration, can be considered which:

(a) reduce the amount of search, and

(b) direct the exploration along pertinent routes.

The derivation of search strategies has been attracting attention in artificial intelligence (AI) research [Akin, 1978, 1986]. The attempt to identify a design methodology within a particular domain in practice, as in Marvin and Mackinder's work [1982], also appears to imply this purpose. Akin, for example, observed search strategies in the behaviour of architectural designers at work in an architectural office, and proposed a descriptive model of them in terms of an information processing mechanism [Akin, 1978]. He characterised the designers' behaviour in terms of problem-restructuring and problem-solving; developed an information processing model for architectural design [Akin, 1986]; and implemented a computer-based tool for room layout design using the production system [Akin et al., 1988a].

In the scope of design as problem-solving, the utilisation of computers has resulted in the two most prominent applications of computer-aided design (CAD) techniques: simulation and optimisation [Coyne et al. 1989].

(a) Optimisation

Optimisation seeks not only a design solution but the potential 'best' solution for a given goal, whereas simulation is used to predict the performance of a given design. In optimisation, unlike in the simulation approach, a design is not postulated. The optimisation approach assumes that a design, i.e. a set of design decision values, and its performances, are related by a function, or functions. The performance criteria are used to guide the search through the design decision space in order to find the solution which best meets them.

If the design problem is mathematically formulated in terms of design decision variables, performance variables and the functions between them, the optimisation approach could provide a powerful search strategy as mathematical techniques such as 'hill-climbing' can be employed, and may lead to automated design. On the assumption that a design process is essentially computable, computer-aided design (CAD) became possible when the design was reduced to the process of computing values within a well-defined problem-solving framework. Because of this emphasis on numerical computation, however, the optimisation approach has failed to comprehend a whole design process in practice. Considering actual design activities, not all design decision and performance variables can be quantified, and the causal relationships, or the functions representing mapping, between these two kinds of parameters are not always clear. In addition, mapping does not always correspond one to one, so that several alternative solutions may exist for a set of performance requirements. Also, it is very debatable as to whether design should become an automated process and obviate the need for the human operator.

(b) Simulation

In simulation, once the values of design decision variables are posited, the values of performance variables are, for example, obtained by means of calculation. Then, these performance values need to be evaluated against given criteria to determine whether or not they are satisfactory. If not, the values of some of the design decision variables are modified, and the simulation-evaluation process will be repeated until a satisfactory performance level is reached.

Since the relationships between the performance and design decisions are not always obvious, there is no way of telling how good the proposed design is until the design proposal is simulated and its performance evaluated. In order to reach a satisfactory design, the search process requires the feedback of the evaluation results. This feedback may often need to be analysed to modify the design simulated previously. It should be noted that the evaluation is separated from the interpretation of a design. It can also be said that simulation only translates a potential design solution, i.e. a set of design decisions, into its performance characteristics within the search process.

3.4.2 Knowledge and the development of a design solution

The ultimate purpose of the design activities is to develop such values of the *design decision variables* that the *performance variables* will eventually have their values within the *design criteria.* Once a certain set of *design objectives*, or *performance requirements*, and an initial proposal have been set up, a designer may try to improve the values of the *design decision variables*, i.e. a design solution, using his/her expertise. During the course of the design process, the designer also examines whether or not a certain design, i.e. a description of an artefact formed by a set of values assigned to these *design decision variables*, satisfies the set of *design criteria.* This operation involves predicting the performance of the artefact being designed.

In terms of the mapping between *design decisions* and *performance*, design activities could be undertaken in two directions: from the *performance space* to the *design decision* *space*, and vice versa. In both cases, there may be direct and/or indirect relationships between required performances (expressed within the performance space), and a design, i.e. a set of design decision values described within the design decision space. The relationships between the *performance variables* and *design decision variables* are not always obvious, however. Such causal relationships may be represented as a kind of black box (see Figure 3.2). In order to undertake the design activities, it may be necessary to know a number of these possible relationships: to derive a set of appropriate values about *design decision variables* from *design objectives* (see Figure 3.4 (a)), and to determine whether a set of design decision values satisfy the *design criteria* (see Figure 3.4 (b)). So, it is considered that "knowledge" is vital to derive a satisfactory design. In this sense, the "knowledge" may involve that regarding the physical and/or mathematical descriptions of the behaviours of a building (what Mackinder and Marvin [1982] describe "experience of how a building is put together" (see Appendix A of this thesis)), as well as heuristic or experiential knowledge. It is recognised that designers gain more knowledge and understanding about these relationships as they become more experienced. In other words, it is understood that the relationships between *design decisions* and *performance* could be represented by knowledge. Therefore, the use of intelligent knowledge-based system techniques could be advantageous when developing descriptions of design activities.

Chapter 4

Chapter 4

A FRAMEWORK FOR INTER-DISCIPLINARY BUILDING DESIGN WORKING AND A CHECKLIST

This chapter will focus on the development of a framework for inter-disciplinary design working. In Section 4.1, the development of a framework of the building design process is discussed in terms of the use of a checklist. In Section 4.2, the ill-defined nature of the design activity is tackled and a rational basis for modelling the process is developed. Building design work is considered as a hierarchy of a set of sub-problems, called "*design issues*", and the individual design activities, called "*design tasks*", which originate from these design issues. The design issues and design tasks are identified, with particular reference to daylighting and lighting design, and are derived mainly from consideration of the RIBA *Plan of Work* and British Standard BS8207 '*Code of Practice for Energy Efficiency in Buildings*' as well as the CIBSE 'Application Manual *Window Design*'. In Section 4.3, firstly, stereotypes, or forms, of office buildings are discussed, and examples of stereotypes for daylighting design are proposed. Then, a framework for inter-disciplinary design working interactions is developed, based upon this description of the building design work, in terms of the *design variables* and the relationships between them, in relation to the three-space model proposed in Chapter 3. In order to establish a sequence of design decision-making steps with cross-references, the relationships are described in matrices and studied, utilising graph theory. The design knowledge used has been extracted mostly from published materials. Finally, the framework is described in a checklist form in Section 4.5.

4.1 Inter-disciplinary Design Working and the Checklist Approach

In the field of building design, designers, architects in particular, may have stereotypes, which can provide a 'starting point' for the development of their design, reflecting social trend and technological development, as a part of their expertise [Hawkes, 1974]. Design methodologies, i.e. the manners in which designers tackle their design problems, appear to vary superficially between designers as a consequence of their different experiences, design philosophies and personal preferences. Similarly, since the brief, e.g. requirements and constraints, of every design project will be unique, design routes taken by individual designers may vary from one project to another. Therefore, a number of people working in the field of building design, especially architects, may claim that there is only a loose structure upon which the building design process may be constructed. Also, it is often presumed that only unrestricted circumstances provide opportunities for cultivating original ideas for outstanding buildings, and that any prescribed procedures can severely restrict design activities.

Where there is no prescribed procedure, however, it is perceived that only those designers who have considerable experience regarding both stereotype and working procedure are able to complete their design projects successfully. But, it is reasonable to assert that an excessive reliance upon experience presents a risk of introducing or reinforcing existing prejudices which might lead the designers to inappropriate decisions and/or errors of omission, when faced with new ideas, materials or technologies.

Those who have little design expertise are likely to suffer difficulties in obtaining an appropriate initial proposal since they may not have a good deal of knowledge regarding available stereotypes. For those who have little knowledge about how to carry out, their design tasks frequent backtracking is likely to occur. Such difficulty and backtracking tend to cause a low productivity of the design process. This is likely to be inevitable in developing a quality-assured design unless a prescribed procedure is followed which orders their design tasks appropriately. They may therefore have to rely upon particular design methodologies described in a prescriptive process.

As these designers acquire more experience, i.e. develop design methodologies, they may well become able to work without consciously relying on such frameworks. Consequently, they might perceive that they are not working within a structured process while carrying out their design tasks. An additional problem inherent in this 'unconscious' approach to design is the lack of a common understanding of, or 'language' existing between design team members to describe the process. In other words, there is no foundation on which their interactions can be built. Having becoming experienced, however, it is possible that designers still follow a particular procedure, unconsciously. To promote inter-disciplinary design working, a common foundation, or framework, enabling the design team members to work together needs to be established.

This view can be supported by Mackinder and Marvin's research [1982], which implies that designers tend to manage their work by using certain procedures, such as that described by the RIBA *Plan of Work*. This suggests that the RIBA *Plan of Work* can be viewed as one method by which the building design process can be managed and which designers tend to follow either consciously or unconsciously, and that it is possible to ascertain a framework relating to design methodology. In other words, a framework for inter-disciplinary building design working could be developed based upon the management procedures outlined by the RIBA *Plan of Work*.

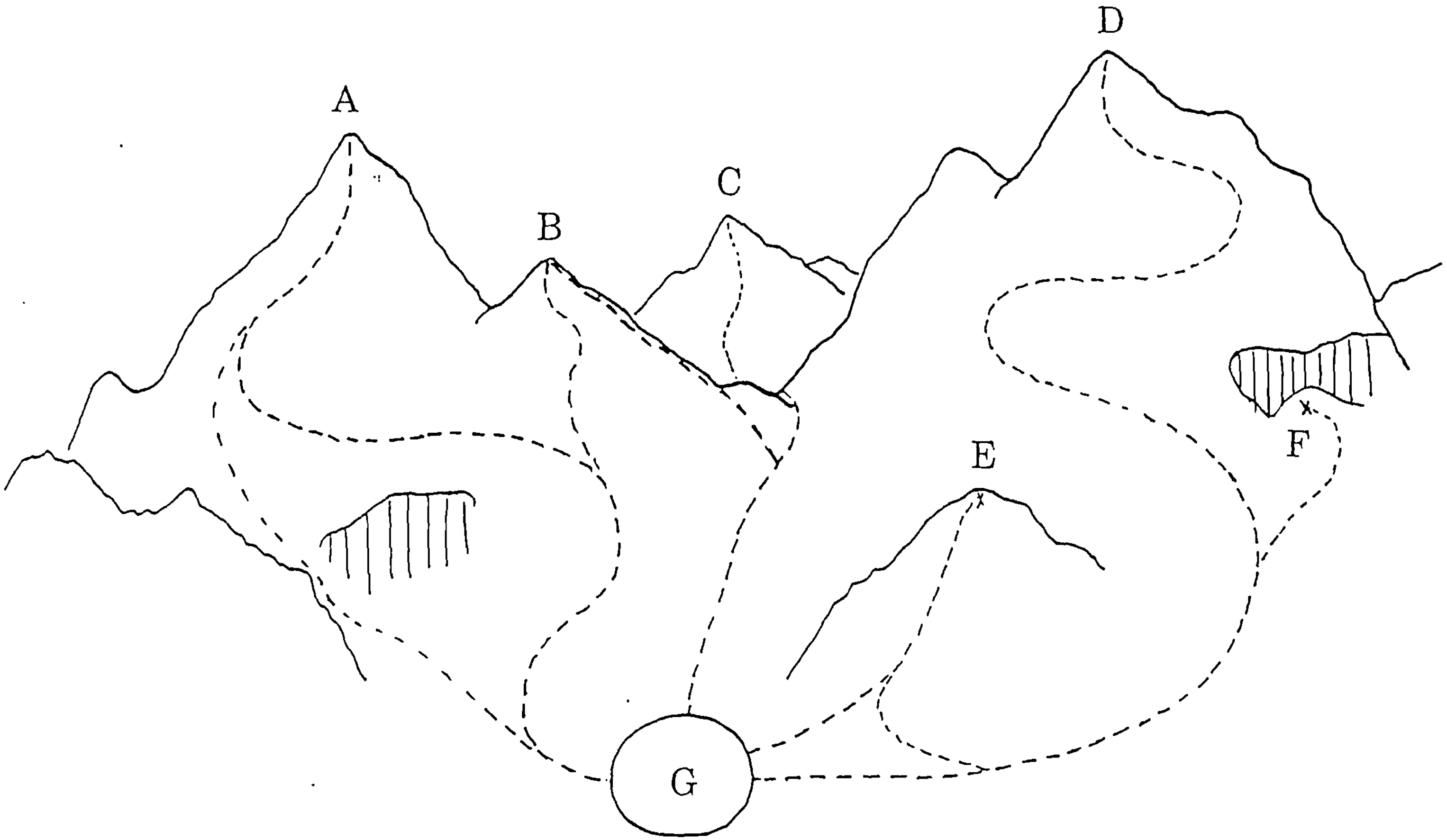
In order to provide a framework for inter-disciplinary design working, it was decided to attempt the description of describe a sequence of vital design decision-making steps undertaken during the building design process in the form of a checklist. The challenge was to draw a *'map'* of the common features of the design processes, or a sequence of design decision-making, i.e. decisions to be made, along with what information is required, and when, within the framework described by the RIBA *Plan of Work*. This can provide cross-references between design aspects, important to the various disciplines regarding a particular design decision.

To accommodate both the functional and aesthetic requirements of a building, the building components such as walls and windows need to be specified and integrated from a multi-disciplinary point of view, using appropriate information, during the design process. It is thought to be important that design decisions are made in a manner and sequence that ensures that serious problems are not caused to some members of the design team at a later stage in the process. The use of a checklist could reduce the risk of 'errors of omission' occurring during critical design considerations. This function would act to reduce the risk of possible building or systems failures, and also help to promote inter-disciplinary building design working.

During periods of rapid technological developments and changing regulations, building components and construction techniques and the constructions developed using them enable designers to make various new design approaches. The checklist approach itself may not be able to provide immediately sufficient information regarding the latest technological developments, however, the designers could be alerted to pertinent design issues while checking vital decisions. The use of the framework could help the effective use of and further expansion of a design information database. An intelligent knowledge-based systems approach is capable of accommodating such developments by updating knowledge-bases, which are separated from the system's control/inference functions, as explained later in Chapter 5.

The function of a checklist could be compared to a map showing features in an unfamiliar area, such as mountains, where there may be a number of potential routes to a summit (Figure 4.1). The map will be used by climbers to seek an appropriate route without losing their way. Once a route has been established, they may well continue to use it on other occasions. Being more familiar with this route and its geography, the climbers will become more aware of signs and check points on the way, and the "map", i.e. their knowledge of the terrain, will be imprinted on their minds. As a result, the physical map may become less-frequently used. When the climbers want to reach a different destination, or have to change their route as a result of an avalanche, for example, the map will be required once again to attain their objectives. The map also needs to be up-dated to allow climbers to take advantage of any geographical changes, including developments such as new bridges and tunnels.

The use of a checklist developed upon a framework, however, implies a degree of normalisation which may act against a perceived flexibility of design activities. If the degree of normalisation is too high, the use of a checklist could leave designers feeling constrained and so reduce the opportunities for innovative thinking. A likely outcome could be that the designers might be unwilling to follow such a procedure, claiming loss of control of the design process. Even if the procedure, formalised by the checklist, is accepted, the design activities are likely to be perceived as limited and driven by prescription. Therefore, the controlling, or supervisory, function of a developed software, which will be described in Chapter 6, must be subtle in its operation and must certainly allow and promote choice.



A, B, C, D: Peaks, i.e. potential goals;
E, F: Dead end, i.e. failure;
G: Starting point, i.e. initial state

Figure 4.1 Allegory of mountain climbing

An attempt to map the diverse considerations required regarding energy aspects of building design has been made in British Standard BS8207 '*Energy Efficiency in Buildings*'. British Standard BS8207 was developed to indicate the energy related issues to be considered at particular points within the design process stages as described by the RIBA *Plan of Work*. To pursue the checklist approach further in this project, the following steps were undertaken:

(1) considering the building design process beginning as an ill-defined problem, a rational description of the building design work was established, in which vital design activities were identified and organised within a hierarchical structure (Section 4.2);

(2) looking at the features of office buildings completed recently, a number of stereotypes were identified and discussed in relation to the major concerns of the design projects, i.e. energy efficiency and internal environmental comfort, and further examples of stereotypes were considered with particular reference to daylighting design (Section 4.3.1);

(3) in relation to the 3-space model proposed in Chapter 3, a framework for inter-disciplinary design working was then developed based upon the rational description of the building design work, where the building design process is described in terms of the *design variables* and relationships between them (Section 4.3 and 4.4); and finally,

(4) organising the design information extracted from published materials presented in Appendix D, the framework which provides a favourable sequence of design decision-making as well as the cross-references for design decision-making, was developed, and, consequently, a checklist for inter-disciplinary design working with particular reference to daylighting and lighting design aspects was established (Section 4.5).

The framework will become the foundation upon which a computer-based design information aid is developed using the intelligent knowledge-based systems techniques, to demonstrate how the building design might proceed with aid of a checklist. This will be discussed in Chapter 5 and 6.

4.2 The Development of a Rational Description of the Building Design Work

In this Section, a rational description of building design work is established. Firstly, the manner in which professional designers deal with design is discussed. Then, building design is described as a set of "*design issues*", for which design methodologies are considered to be relatively well-established. Individual decision-making processes originating from these *design issues* are called "*design tasks*". Consequently, it is possible to organise design activities within a hierarchical structure. Finally, the *design issues* and *design tasks* particularly related to daylighting and lighting design are identified, within the stages described by the Royal Institute of British Architects, RIBA, *Plan of Work* and British Standard BS8207 '*Code of Practice for Energy Efficiency in Buildings*', as well as through reference to the Chartered Institution of Building Services Engineers, CIBSE, 'Application Manual *Window Design*', BS8206 '*Lighting design for Buildings*' and '*Code for Interior Lighting*'.

4.2.1 Building design:- an ill-defined activity

As discussed in Section 1.2 of Chapter 1, designing a building can be considered as an "ill-defined" as well as a "purposeful" or "goal-directive" activity. An ill-defined activity is usually complex, and involves the following characteristics:

(a) the objectives and targets are often unclear at the beginning of the design process;
(b) there is no straightforward or overt process to follow; and
(c) partial solutions, which are developed in relation to particular aspects of the problem, need to be integrated into a final solution, while resolving the conflicts between them.

To solve such an ill-defined problem like designing a building, therefore, the experts, i.e. professional designers such as architects, must be capable of:

(1) setting up adequate design targets,
(2) redefining the ill-defined problem into a set of well-defined sub-problems and resolving them, and
(3) re-assembling partial solutions into a general solution for the entire problem.

In the early stage of this project, a case study on a building design process was carried out by observing a group of designers working on a school building design project. This is reported in Appendix C of this thesis. During the case study, it was observed that the design group's working method reflected the three attributes of tackling an ill-defined problem, i.e. establishing their design objectives at the beginning, defining a set of sub-problems in terms of particular aspects of the building design, and developing the final design proposal by integrating the partial solutions for these sub-problems. Each of these attributes is explained below, in relation to the design study (described in Appendix C) and based on the RIBA *Plan of Work*.

(1) Setting up adequate design targets

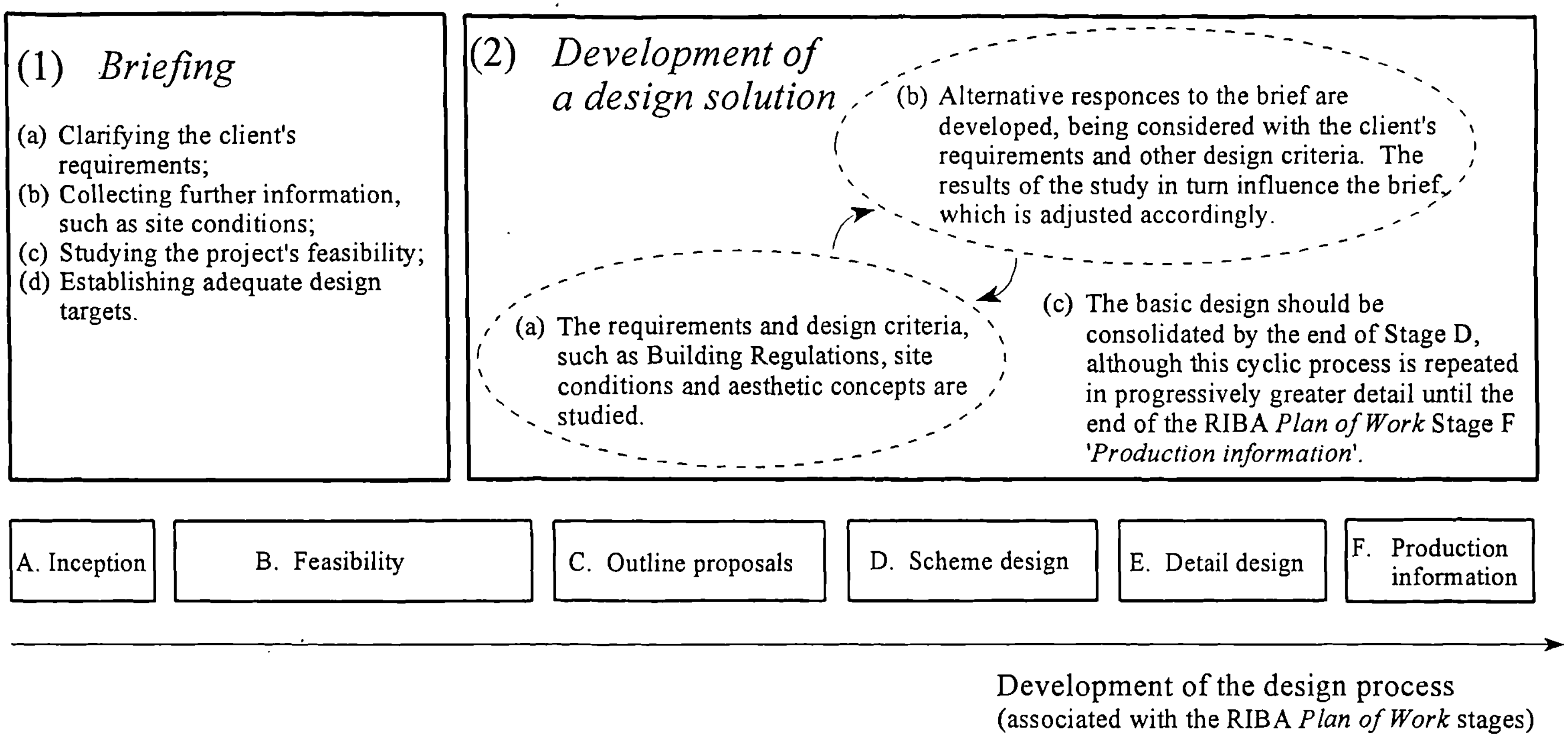
The more detailed objectives of a design project are often unclear at the beginning of the design process, and need to be established before exploring design solutions. Having studied the building design stages according to the RIBA *Plan of Work*, as explained in Chapter 2, it became clear that the strategic phase of the building design process could be divided into two features (See Figure 4.2):

(i) *Briefing*

To establish a brief, the client's requirements are clarified, and further information, such as site conditions, is collected. A feasibility study follows these activities so that adequate design targets can be established.

(ii) *Development of a design solution*

The brief is put into practice with alternative design options, being considered with the client's requirements, structural and services engineering considerations, other design criteria such as Building Regulations, and unifying aesthetic concepts. The study of the requirements and design criteria is continued at the same time, and the results of the study in turn influence the response to the brief, i.e. the design proposals, which are adjusted accordingly. This cyclic process is repeated in progressively greater detail until the scheme design is completed at the end of Stage D "Scheme design" of the RIBA *Plan of Work*. Further detailed design can then proceed in the following stages hopefully without the need for excessive back-tracking.



(1) *Briefing*

(a) Clarifying the client's requirements;
(b) Collecting further information, such as site conditions;
(c) Studying the project's feasibility;
(d) Establishing adequate design targets.

(2) *Development of a design solution*

(b) Alternative responces to the brief are developed, being considered with the client's requirements and other design criteria. The results of the study in turn influence the brief, which is adjusted accordingly.

(a) The requirements and design criteria, such as Building Regulations, site conditions and aesthetic concepts are studied.

(c) The basic design should be consolidated by the end of Stage D, although this cyclic process is repeated in progressively greater detail until the end of the RIBA *Plan of Work* Stage F '*Production information*'.

Figure 4.2 Two features of the strategic phase of the building design process: "*Briefing*" and "*Development of a design solution*".

Here, *Briefing* represents the activities needed to identify the important requirements and constraints, and set up adequate design targets. In order to handle a design project successfully, it is important for the designers to collect all the fundamental information required, even though this may be limited, and to establish design targets swiftly and appropriately. It is also important to establish a definite agenda by the end of Stage B "Feasibility" by fixing the basis on which design ideas are to be developed. In other words, the brief should ideally not be changed after Stage B.

(2) Redefining the ill-defined problem into a set of well-defined sub-problems and solving them

In order to solve an ill-defined problem, where no straightforward path to a solution exists, it is necessary to redefine it into a sequence of sub-problems, for which solution principles and design methodologies are well-established. Akin carried out protocol studies by observing and interviewing architects at work [Akin, 1986, 1988b]. He describes this as follows:

> "given a design problem, the architect first sets out to identify the important requirements of the problem. Then he selects from these requirements a well-defined subset of design problems: for example configure the roof shape, develop an internal layout, and so on." [Akin, 1988b, p.180]

This activity is called "*problem structuring*", in which experienced architects, compared to lay people, display remarkable skills [Akin, 1988b]. According to the case study which is described in Appendix C of this thesis, it was observed that the design group undertook its design project by dealing with a set of sub-problems, such as *building form*, *roof form*, *internal layout*, *construction type*, and *daylighting*, using computer-based design tools.

Generally, designers need to be good at not only solving well-defined sub-problems, but also they should be capable of redefining (structuring) the ill-defined problem. The experts in a particular field, e.g. architects, may often use particular strategies which neither lay people nor other professionals possess. According to Akin, for designing an internal layout, for example, the experienced architects created "*scenarios*" to organise the parts of the architectural program into a plausible operational order [Akin, 1988b]. Here, the *scenarios* defined the principal proximities, hierarchical relationships, privacy, and access patterns which have to exist between parts of the program. They described organisational ideas, such as a hierarchical office or an open classroom school, where a consistent behavioural idea is in evidence. They provide for the architects topological templates which are adaptable to different requirements. Such a strategy was also found to provide conceptual constructs. Using *scenarios*, these architects could define physical relationships between spaces without the need for fixed geometric attributes. Within the case study, as described in Appendix C, the use of a '*bubble diagram*' within the case study could be seen as such a *scenario*-like approach.

(3) Re-assembling partial solutions into a general solution: global conflicts and local conflicts

To finalise a design, the solutions of the individual sub-problems need to be restructured into a general solution for the entire problem. Within this process conflicts may arise between these partial solutions and alternatives which have been suggested during the development. Akin pointed out that some of these conflicts are "*local*" in origin, whereas others are "*global*" [Akin, 1988b]. Here, the modifications to remedy a particular *local conflict* do not infringe on any partial solutions other than the one to which they are confined. In other words, a *local conflict* can be remedied by local modifications to the current design within the associated sub-problem. Dealing with "*global*" conflicts may, on the other hand, involve alterations in all or many parts of the design solutions. The protocol studies conducted by Akin revealed that architects who showed good performance in terms of satisfaction of the design requirements, dealt with "*global*" conflicts and alternatives initially before bothering with "*local*" ones [Akin, 1988b].

Having considered the building design as an ill-defined problem, it is suggested that design methodologies should contain the following attributes:

(a) clarifying design objectives,
(b) structuring the design problem into a sequence of well-defined sub-problems, and
(c) restructuring partial solutions into a general solution for the entire problem.

In order to develop a checklist which takes account of the multi-disciplinary aspects of building design working, it was decided that it should be described rationally as a set of well-defined activities, and that a framework should be developed from this description which allows design team members to anticipate conflicts, *global* ones in particular. These two aspects are discussed in the rest of Section 4.2 and Section 4.3, respectively.

4.2.2 A rational description of the building design work

(1) *Design issues* and *design tasks*

As discussed in Section 4.1, it was suggested that one of the keys to the promotion of inter-disciplinary design working was a common understanding of the building design process among the design team members, and that this understanding might be established based upon the management stages described in the *RIBA Plan of Work* and British Standard BS8207 "*Code of practice for Energy Efficiency in Buildings*".

It was also noted in Section 4.2.1 that the building design process needs to be redefined as a sequence of well-defined sub-problems, so that the ill-defined nature of the process can be dealt with. Such a sequence of sub-problems may be considered as a basis for the common understanding of the processes involved in building design. It was, therefore, decided to describe building design work in terms of the sub-problems, in order to develop a checklist. This was to be confined to considerations of daylighting and lighting.

The building design process has been considered to comprise several sub-problems. Let us call them "*design issues*" (Figure 4.3 (a)). They may include, for example, "*building form*" or "*window design*". Within the context of the strategic phase of the design process, the *design issues* should also include the activities associated with establishing the design objectives such as "*defining the client's requirements*", "*studying feasibility*" and "*design priorities*". The design methodologies to deal with these *design issues* are relatively well-established. They may comprise a series of design activities through which individual design decisions may be made. In other words, solving a sub-problem (i.e. dealing with a *design issue*) is considered to involve a series of design activities. Let us call these individual decision-making activities "*design tasks*". Considering a particular *design issue*, such as "*window design*", involves making decisions regarding "*glazing type*", "*glazed area*" and "*window shape and position*". During the development of a building design, the *design tasks* can be considered to produce partial solutions for a particular *design issue*, i.e. the design solutions associated with specific components of the building being created. In other words, the partial solutions for the particular design sub-problem, which is also a partial solution of the entire design problem, are developed by undertaking these *design tasks*.

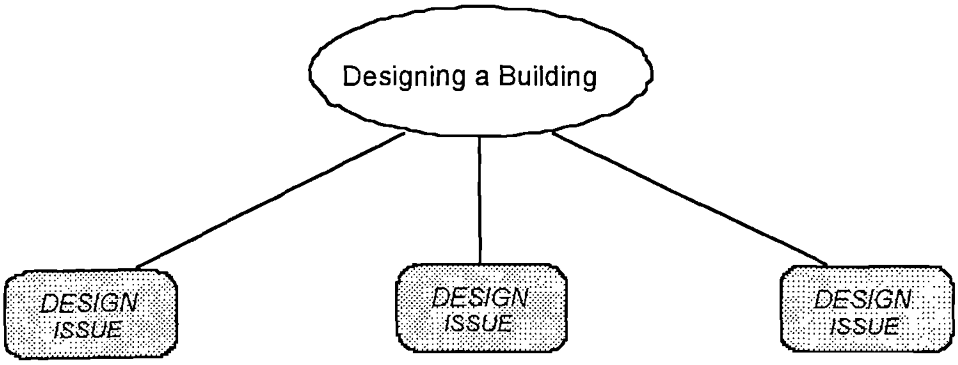


Figure 4.3 (a) Designing a building and its sub-problems "*Design issues*"

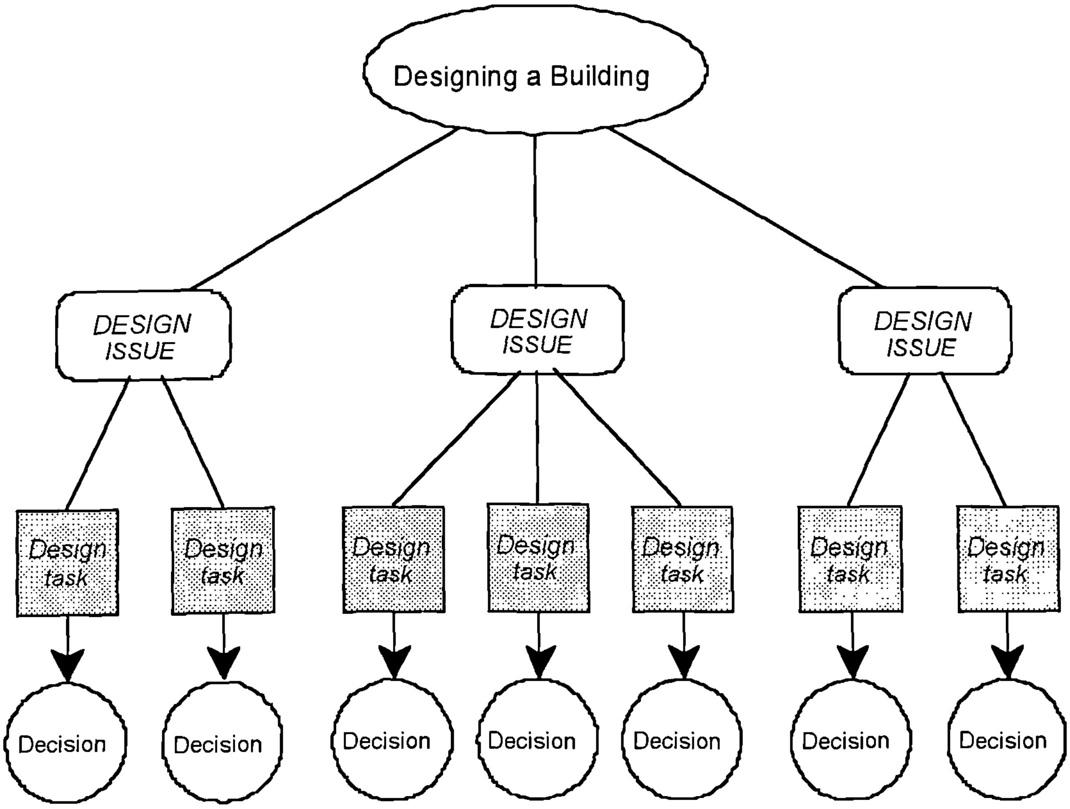


Figure 4.3 (b) A rational description of the design work, which is a hierarchical structure of the " *Design issues*" and "*Design tasks*"

Having defined "*design issues*" and "*design tasks*" as explained above, it is considered useful to define them so that the individual *design tasks*, through which vital decisions are made, originate from one of the *design issues*. This means that each design activity represented by a *design task* can be associated with a particular *design issue*. There are many decision-making activities to be undertaken during the design process, and the building design work can be described as a hierarchical structure of the *design issues* and *design tasks* (Figure 4.3 (b)). Such a hierarchical structure provides a rational description of the building design work, and may be used to prepare a framework for inter-disciplinary building design working.

With regard to design decision-making, for each of the *design tasks* a set of design criteria should exist in order that potential decisions may be evaluated (Figure 4.4). To develop a checklist for building design working, it is necessary to prescribe these design criteria related to the *design tasks*, so that designers can make individual decisions with a view to a wide understanding or knowledge of the likely implication of particular decisions.

The decisions made through the *design tasks* are, meanwhile, still partial solutions in terms of a particular *design issue*. In order to integrate them into an entire building design, any global conflicts which might arise between these partial solutions have to be remedied before dealing with the local ones (Figure 4.5 (a)). From the point of view of inter-disciplinary working, it is necessary for individual team members to carry out each *design task* while being aware of the potential conflicts that may exist with other design activities. In this sense, it is advantageous to pre-empt these potential conflicts, particularly global ones. For this purpose, a rational description of the building design work can provide an appropriate platform where both global and local conflicts between the decisions made as a result of the *design tasks*, i.e. between the partial solutions, could be dealt with. This will occur at the different levels of the hierarchy: *global conflicts*, which require modifications affecting the overall design, will be considered at the *design issue* level, whereas *local conflicts* will be dealt with at the *design task* level within the associated *design issue* (Figure 4.5 (b)). A framework for inter-disciplinary building design working will be developed based upon this rational description in Sections 4.3 and 4.4.

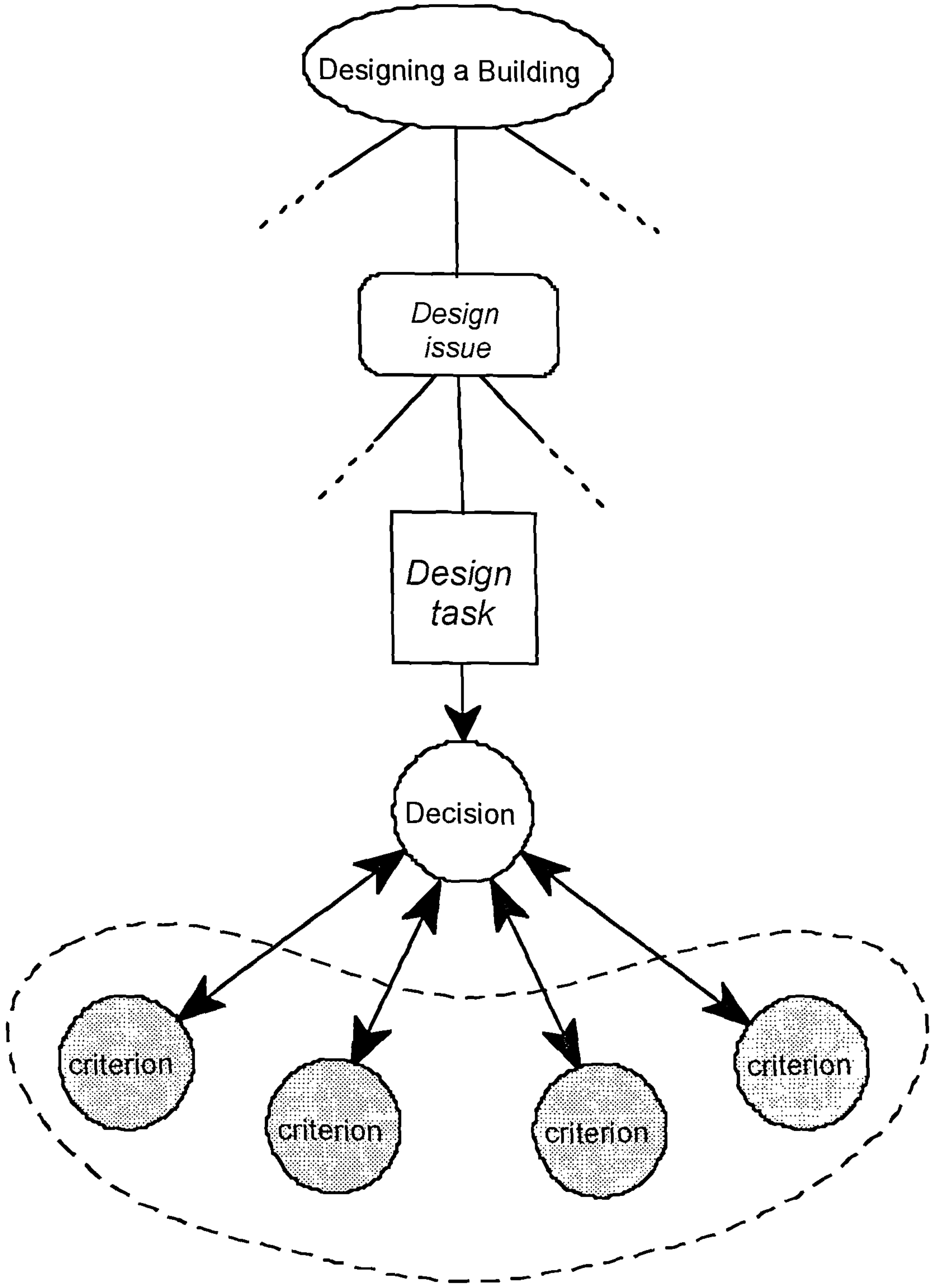


Figure 4.4 *Design task*: decision-making and its related design criteria

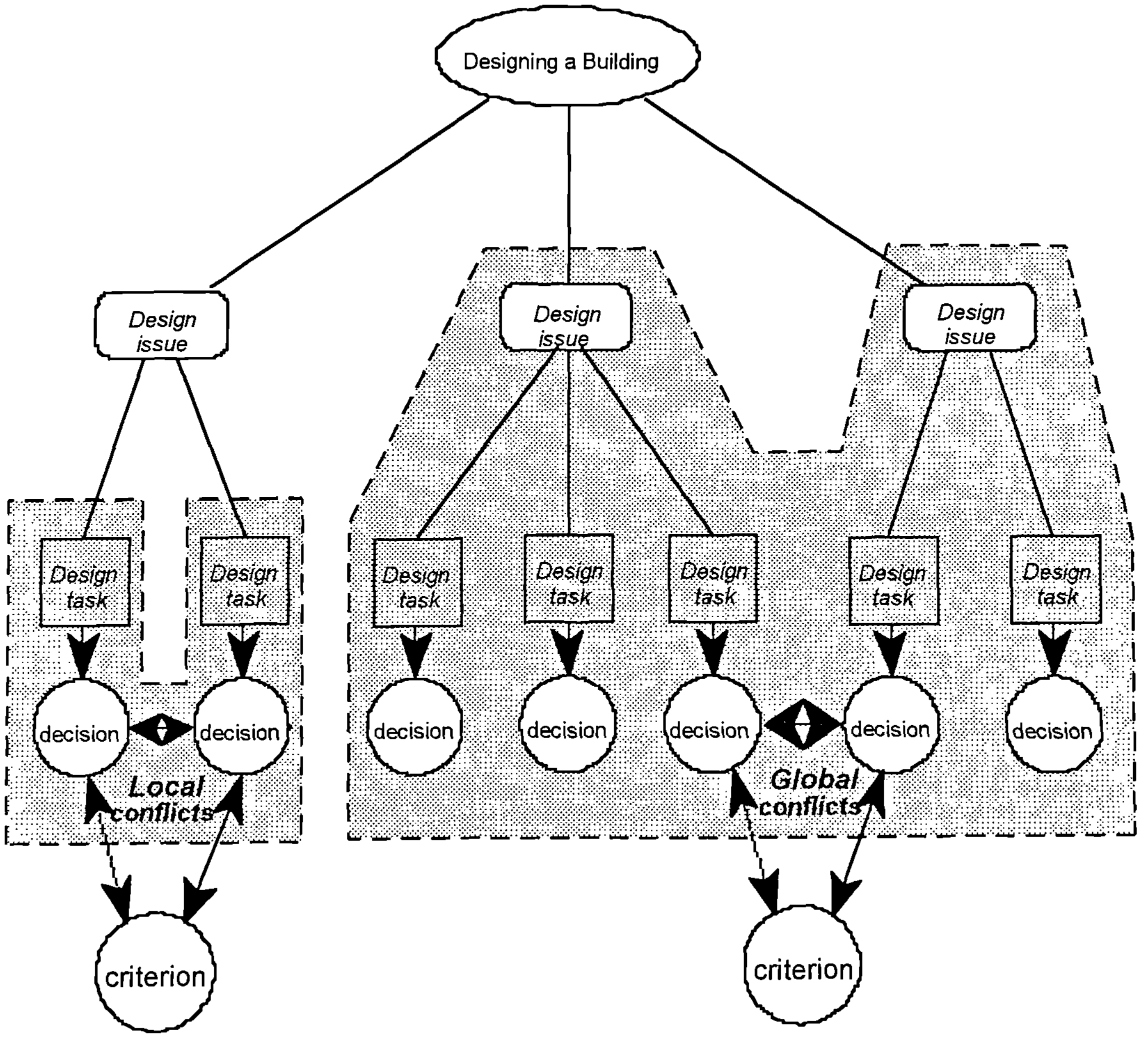


Figure 4.5 (a) Conflicts between partial solutions:
Global conflicts may require modifications in nearly all parts of the solutions (decisions), whereas local conflicts are remedied by local modifications at the design task level.

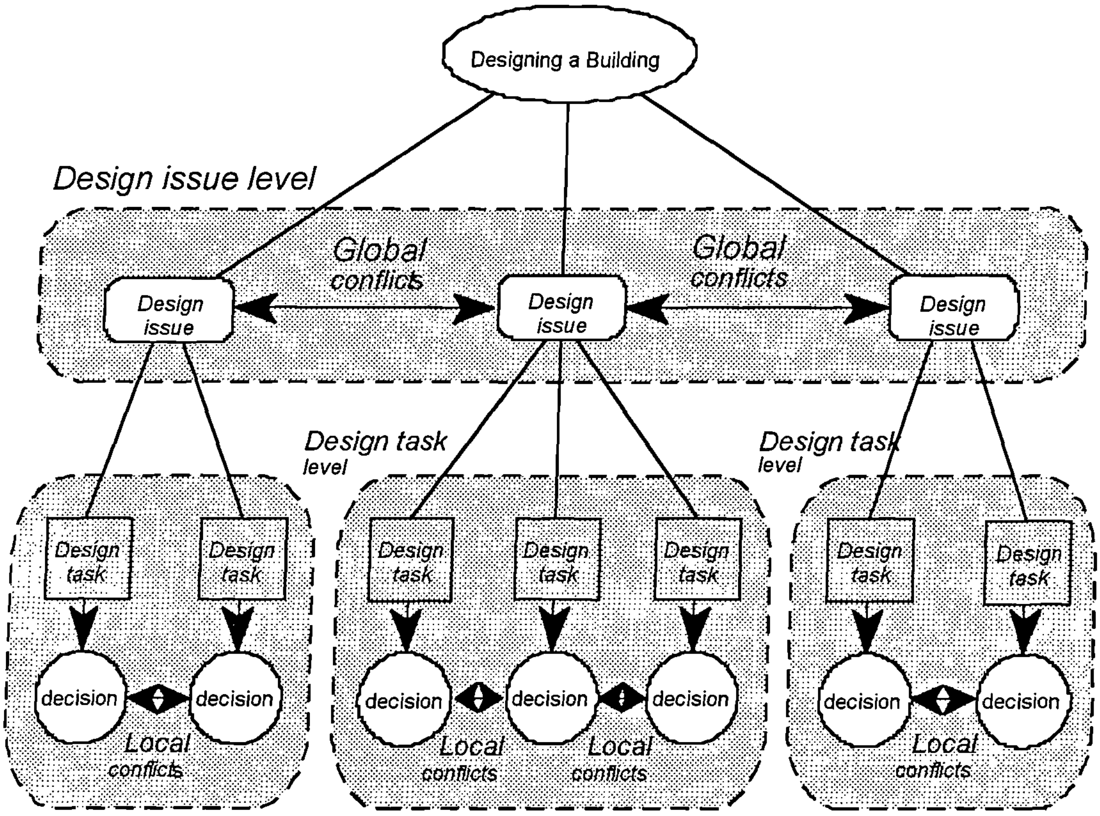


Figure 4.5 (b) Conflicts between partial solutions, and the hierarchical structure of the design work: global conflicts may be considered at the *design issue* level, whereas local conflicts are remedied at the *design task* level.

Table 4.1 The design decisions associated with daylighting and lighting design aspects (reproduced from Table 1 in BS8207 [1985])

Design decisions	RIBA Plan of Work stages					
	Briefing		Sketch plans		Working drawings	
	A. Inception	**B. Feasibility**	**C. outline proposals**	**D. Scheme design**	**E. Detail design**	**F. Production information**
1. Agree energy objectives and criteria	—					
2. Define uses, including changes of use, to be allowed for	—					
3. Identify use factors affecting zoning	—	—				
4. Select environmental standards	—	—				
5. Examine site suitability, restrictions, alternatives	—	—				
6. Consider building shape and its arrangement on the site		—	—			
7. Decide main methods of ventilation		—	—			
9. Design fenestration taking account of lighting and internal requirements		—	—	—	—	
18. Design artificial lighting and controls, taking account of daylight availability and lighting demand patterns				—	—	—

(2) Defining the *design issues* and *design tasks*

For this study, the building design process was considered, with particular reference to daylighting and lighting design. Table 4.1 is an extract from Table 1 of BS8207, which illustrates the design decisions associated with the daylighting and lighting design aspects, and the timing of these decisions in relation to the design stages described by the RIBA *Plan of Work.* The design decisions shown in Table 4.1 were, however, found insufficient to accommodate appropriately the *design issues* within the inception and feasibility stages in particular, because BS8207 is mainly concerned with improving energy efficiency through the development of a building design, and, as a result, involves little detailed information about setting up appropriate design targets in terms of daylighting and lighting design aspects. The building design process was therefore examined with particular reference to daylighting and lighting design aspects.

Twelve *design issues*, and *design tasks* were defined for this project based upon the knowledge contained within the Chartered Institution of Building Services Engineers, CIBSE, 'Application Manual *Window Design*' [1987], British Standard BS8206 '*Lighting design for Buildings*' [Part 1, 1992; Part 2, 1985] and CIBSE '*Code for Interior Lighting*' [1984], as well as the RIBA *Plan of Work* and BS8207, as follows:

Design issue (1) 'General outline of requirements'

The client's requirements, which are often unclear at the beginning of the design process, are clarified. The client's initial brief may involve the aim of the project, cost range and time table. The client's initial brief needs to be evaluated to ensure it provides adequate statements of his/her requirements and intentions. The *design tasks* associated with this issue are as follows:

(a) During initial meetings, the designers have to clarify the client's requirements in terms of:
  (i) the aim of the project,
  (ii) cost range (budget), and
  (iii) time table; and

(b) At the same time, the designers should collect as much relevant information as possible concerning:
  - (i) use of the building,
  - (ii) accommodation (use/functions of the spaces),
  - (iii) activities carried out within the spaces,
  - (iv) visual tasks,
  - (v) occupation patterns.

Design issue **(2) 'Design objectives'**

Obtaining further information as necessary, design objectives are established, including:

(a) energy targets;

(b) primary performance requirements, such as thermal comfort and visual environment criteria; and

(c) construction cost criteria (cost range).

Design issue **(3) 'Context of the scheme'**

The context of the scheme is established within the requirements of internal and external constraints, legal aspects and technical problems. Consideration of site conditions is one of the most important concerns relating to this issue. It involves examination of:

(a) Physical constraints:
  - (i) boundaries;

(b) External environment:
  - (i) daylight availabilities,
  - (ii) sunlight duration,
  - (iii) view/scenery,
  - (iv) noise sources,
  - (v) physical pollution,
  - (vi) ambient climate; and

(c) Legal aspects:
  - (i) local authority and statutory regulations.

Design issue **(4) 'Feasibility study'**

Considering the building's functions, quality and the needs of the client and users, the feasibility of the project is assessed in terms of cost, technical practicality, social effects and aesthetic expectations. The *design task* related to this issue is to study whether or not the client's requirements and the design objectives are viable in functional, technical and financial terms; and if not, the designers need to discuss them with the client with a view to adjusting the brief.

Design issue (5) **'Performance criteria: environmental standards'**

Having carried out the feasibility study, performance criteria, or environmental standards, are established as design performance targets, which will be design criteria against which design solutions are assessed. The *design task* is to determine the performance criteria, taking account of statutory requirements as well as recommendations from professional institutions such as CIBSE, in terms of:

(a) Daylighting and lighting aspects, including the requirements for
  (i) illuminance level,
  (ii) illuminance uniformity,
  (iii) target average daylight factors (if daylight is used)
  (iv) colour properties, i.e. colour correlation temperature and colour rendering;
(b) Thermal comfort criteria;
(c) Acoustic considerations regarding allowed noise level within rooms; and
(d) Ventilation / air quality requirements within the building.

Design issues (6) **'Design approach / priorities'**

Design approaches are determined in terms of daylight, sunshine, view, ventilation and noise insulation priorities, before any concrete design ideas are developed. Therefore the *design tasks* of this issue should consider:

(a) daylight priorities;
(b) sunshine priorities regarding the thermal behaviour of the building;
(c) view priorities;
(d) ventilation priorities; and
(e) noise insulation priorities.

Design issue (7) **'Building's arrangement on the site'**

Considering the building form and the site conditions, the position and orientation of the building on the site are examined, in terms of the shadows created by surrounding buildings, possible overshadowing by the building being designed, use of solar energy, daylighting and access to the building. The *design tasks* relating to this issue should consider:

(a) position of the building on the site;
(b) orientation of the building; and
(c) potential effects on the arrangement of internal spaces.

Design issue **(8) 'Building form'**

Taking account of the design approaches determined, possible alternative building forms are developed. They should be considered with regard to arrangement on the site as well as internal layout. Considering the building systems functions such as ventilation and lighting, its thermal response and aesthetic considerations, the *design task* may involve developing:

(a) form of the building, including single/multi-storey;
(b) use of rooflights;
(c) roof shape;
(d) glazing orientation and related glazing areas; and
(e) construction type.

Design issue **(9) 'Internal layout'**

Internal layouts, i.e. accommodation plans within the building, are developed considering the special linking of main areas as well as control zoning. These will be considered in terms of the functions and environmental standards for individual rooms, as well as circulation and public spaces. Attention needs to be paid to room depth, where daylight is used as a main method of lighting. The *design tasks* related to this issue are:

(a) the study of the functional connections of the internal spaces;
(b) the development of an accommodation plan; and
(c) checking the depth of main rooms, if daylight has been chosen as the main source of light.

Design issue **(10) 'Main ventilation methods'**

Depending on the design approaches, main ventilation methods are determined taking account of the impact of the air quality of the external environment, building form, internal layout and window design. The *design tasks* of this issue are therefore to determine:

(a) the use of natural ventilation perhaps via window opening; and
(b) the need for mechanical ventilation or air conditioning.

Design issue **(11) 'Window design / fenestration'**

Designing fenestration is carried out with particular reference to daylighting design as well as the building's energy balance and aesthetics. In other words, it involves the study of daylighting performance in terms of daylight factor, energy balance and thermal comfort in relation to heat loss and solar gain, and view and privacy. The design of rooflights should be prior to side window design [CIBSE 'Application Manual *Window Design*', 1987]. The *design tasks* concerning the window design involve:

(a) rooflight profiles, if rooflights have been chosen;
(b) glazing material for rooflights;
(c) glazed area for rooflights;
(d) number and position of rooflights;
(e) area and dimension of individual rooflights;
(f) primary function of windows;
(g) glazing material for side windows;
(h) glazed area for side windows;
(j) window shape and position;
(k) shading devices; and
(m) reflectance of the interior.

Design issue **(12) 'Artificial lighting installation'**

The design of artificial lighting installation has to be carried out taking account of the energy balance of the building as well as the visual environmental requirements. The *design tasks* of this issue include:

(a) identifying the functions of artificial lighting in relation to daylighting;
(b) selecting lighting systems;
(c) selecting lamp types;
(d) selecting luminaires;
(e) arranging the luminaires; and
(f) selecting lighting control system.

Table 4.2 shows the *design tasks* along with the *design issues* from which they originate. These 12 *design issues* are illustrated in relation to the RIBA *Plan of Work* stages in Figure 4.6. In this illustration, *design issues* (1)-(5) are associated with the job of dealing with an ill-defined problem, i.e. setting up adequate design targets; whereas *design issues* (6)-(12) are related to the development of a design, i.e. solving sub-problems (*design issues*) and reassembling them into a general solution.

Table 4.2 *Design issues* and *design tasks* (1/3)

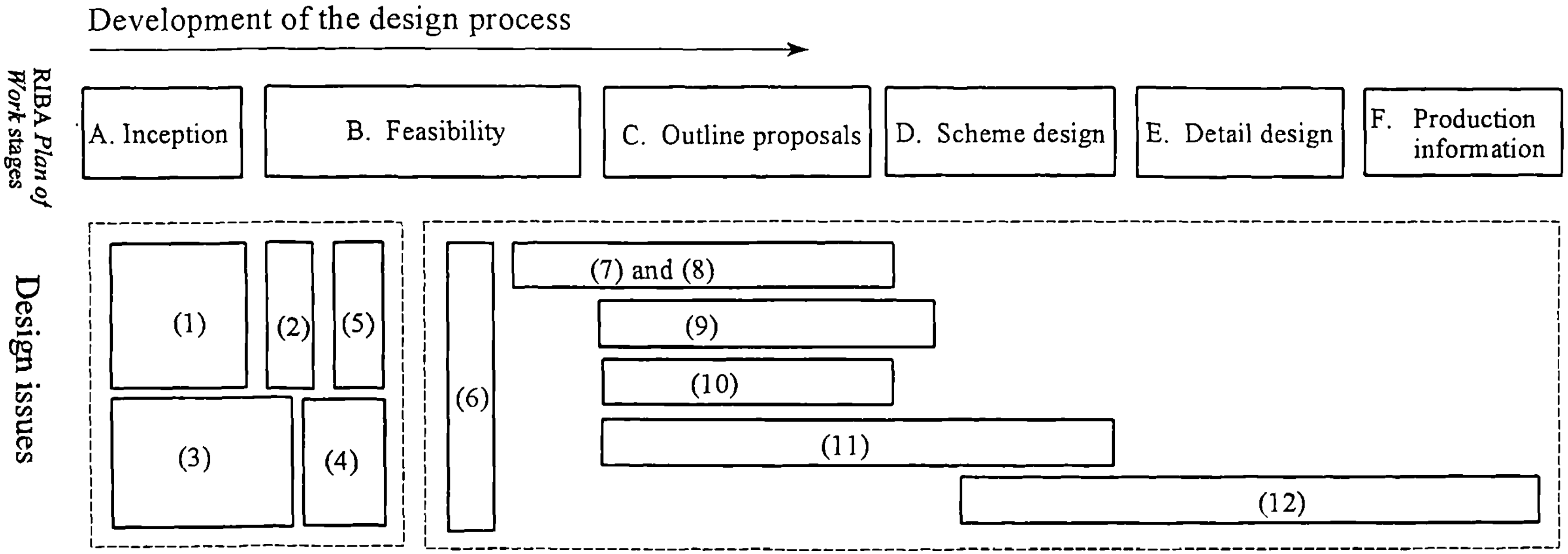
Design issue	*Design tasks*
(1) General outline of requirements	(a) Client's requirements in terms of: (i) aim of the project (ii) cost range (budget) (iii) time table (b) Information concerning: (i) use of the building (ii) accommodation (use / functions of the spaces) (iii) activities carried out within the spaces (iv) visual tasks (v) occupation patterns
(2) Design objectives	(a) Energy targets (b) Primary performance requirements such as (i) thermal comfort (ii) visual environment (c) Construction cost criteria (cost range)
(3) Context of the scheme	(a) Examining physical constraints in terms of boundaries (b) Studying external environment in terms of : (i) daylight availabilities (ii) sunlight duration (iii) view/scenery (iv) noise sources (v) physical pollution (vi) ambient climate (c) Studying legal aspects, such as (i) local authorities and (ii) statutory regulations

Table 4.2 (continued) *Design issues* and *design tasks* (2/3)

Design issue	*Design tasks*
(4) Feasibility study	Assessing the client's requirements and the design objectives in terms of cost, technical practicality, social effects and aesthetic aspects; and revising them if found invariable.
(5) Performance criteria: environmental standards	(a) Daylighting and lighting aspects (i) illuminance level (ii) illuminance uniformity (iii) target average daylight factors (if daylight is used) (iv) colour properties (b) Thermal comfort criteria (c) Allowed noise level within rooms (d) Ventilation / air quality required within the building
(6) Design approach / priorities	(a) Daylight priorities (b) Sunshine priorities (c) View priorities (d) Ventilation priorities (e) Noise insulation priorities
(7) Building's arrangement on the site	(a) Position of the building on the site (b) Orientation of the building (c) potential effects on the arrangement of internal spaces
(8) Building form	(a) Form of the building (b) Use of rooflights (c) Roof shape (d) Glazing orientation and related glazing areas (e) Construction type

Table 4.2 (continued) *Design issues* and *design tasks* (3/3)

Design issue	*Design tasks*
(9) Internal layout	(a) Functional connections of the internal spaces (b) Accommodation plan (c) Depth of main rooms, if daylight has been chosen.
(10) Main ventilation methods	(a) Use of natural ventilation (b) Need for mechanical ventilation or air conditioning
(11) Window design / fenestration	(a) Rooflight profiles, if rooflights have been chosen (b) Glazing material for rooflights (c) Glazed area for rooflights (d) Number and position of rooflights (e) Area and dimension of individual rooflights (f) Primary function of windows (g) Glazing material for side windows (h) Glazed area for side windows (j) Window shape and position (k) Shading device (m) Reflectance of the interior
(12) Artificial lighting installation	(a) Functions of artificial lighting in relation to daylighting (b) Lighting systems (c) Lamp types (d) Luminaires (e) Arranging the luminaires (f) Lighting control system



(1) General outline of requirements
(2) Design objectives
(3) Context of the scheme
(4) Feasibility study
(5) Performance criteria: environmental standards

(6) Design approach/priorities
(7) Building's arrangement on the site
(8) Building form
(9) Internal layout
(10) Main ventilation methods
(11) Window design/fenestration
(12) Artificial lighting design

Figure 4.6 The RIBA *Plan of Work* stages, and the *design issues* found in the building design process with particular reference to daylighting and lighting design aspects

4.3 A Framework of Inter-disciplinary Building Design Working

In this section, a framework for inter-disciplinary design working is developed based upon the description of the building design work established in the previous section. Stereotypes are considered to provide a starting point for the design, and the design process may involve the modification or development process based upon the selected stereotype. Having considered Hawkes' paper [1974] as well as articles regarding some office buildings completed recently, examples of stereotypes for an office building are presented. Within the framework, meanwhile, the building design is described in terms of the *design variables*, which are considered to constitute the three spaces of the 3-space conceptual model, described in Chapter 3. Three kinds of *design variables*, i.e. *information*, *performance* and *design decision variables*, which are defined in relation to the three spaces, are considered to represent the *design tasks* of the rational description. Design activities, which may be seen as the mapping between the spaces, are described in terms of the relationships between these *design variables.* These relationships are then described in matrices by examining the building design process with particular reference to daylighting and lighting design aspects. By analysing them, the design criteria for, and potential conflicts between, vital design decisions, as well as an appropriate sequence of decision-making, are identified.

4.3.1 A stereotype of office buildings with particular reference to daylighting design aspects

(1) Stereotypes of office buildings

One of the key points of inter-disciplinary design working is to allow the members of a design team to make decisions at pertinent stages, taking account of possible conflicts, during the design process. A framework for inter-disciplinary design working can be concerned mainly with the various issues which should be considered when a decision is made, rather than with providing the design team with possible solutions. Many of the issues to be considered may be associated with particular design solutions relating to the experience of the disciplines of the team members involved. The starting point for a number of aspects of the design process sometimes may be a stereotype or a rule of thumb.

Hawkes describes in his paper, Types, norms and habit in environmental design [1974], how office building design since the nineteen century has evolved through a series of distinct stereotypes. In this paper, he shows that the stereotypes are redefined as priorities change and technology develops. He points out that, while the quantitative expression of design objectives was barely practised at the beginning of the evolutionary tale, building science has had a profound influence upon the way goals are stated and achieved during the intervening years.

Hawkes also argues that one of the primary driving forces for change is the problem of environmental control [Hawkes 1974; Architects' Journal 1994]. Twenty years ago, large office buildings were almost always fully air-conditioned and had windows with reduced size which were sealed to assist the thermal balance by reducing the effects of solar heat gains and by simultaneously requiring the use of artificial lighting. Many of the office buildings designed these days, however, seem to be different from twenty years ago: open-plan with maximum use of natural ventilation and natural light. The Ionica Building in Cambridge may be an example of such a building that was designed taking account of such considerations [the Architects' Journal, 1 December 1994, p.29-38]. It is clear that there has been a change in the design objectives: not only energy efficiency but also environmental comfort in buildings have become important issues of office building design. Having referred to three articles in the Architects' Journal reporting recently completed buildings, i.e. the Ionica Building in Cambridge [the Architects' Journal, 1 December 1994, pp.29-38], John Menzies' Edinburgh HQ building, [the Architects' Journal, 30 November 1995, pp.29-39], and the new Scottish Office in Leith [the Architects' Journal, 7 December 1995, pp.29-37], it appears that the clients' requirements commonly include:

- an energy-efficient building with open and comfortable interior, i.e. high quality working environment, and
- an open work space to encourage communication which is also highly flexible to allow changes in work teams, technology, and office layout.

The strategy that the design teams developed was to achieve high internal environmental quality in terms of light, temperature, air movement and noise, but using the minimum amount of mechanical equipment and minimum energy consumption. The principle features of the designs were that:

- the buildings have their largest longitudinal axis east-west;
- their relatively narrow floors and clear spans as well as opening windows allow a high degree of natural light and natural ventilation;
- atria / court-yards were arranged to offer glare-free daylighting to the offices as well as providing controllable cross-ventilation;
- building envelopes which were highly insulated but controlled solar gains: thermal mass of the structure was utilised to provide thermal stability and reduce the need for refrigeration to drive air-conditioning;
- Facades were designed to provide excellent daylight penetration while controlling glare and solar gain.

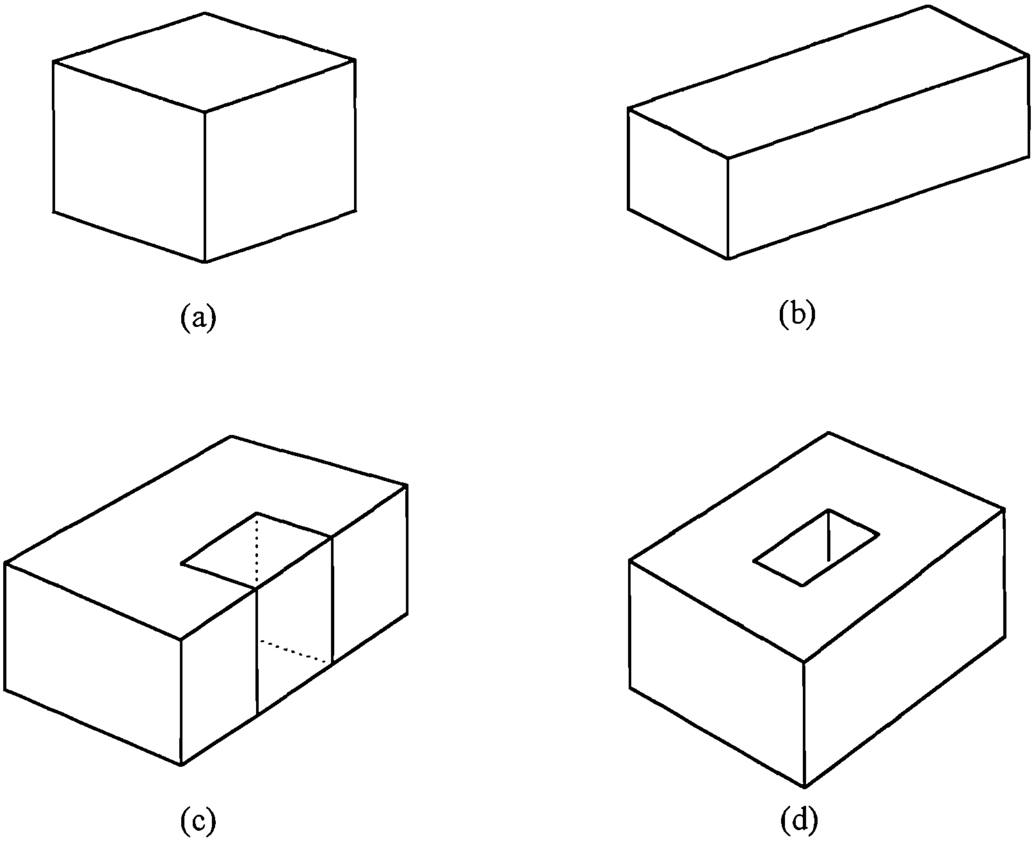


Figure 4.7 Examples of the stereotypes for an office building form

(2) Examples of the stereotypes for an office building form

Having considered Hawkes' paper as well as the buildings such as the new Scottish Office in Leith [the Architects' Journal, 7 December 1995, pp.29-37], the Ionica Building in Cambridge [the Architects' Journal, 1 December 1994, pp.29-38], John Menzies' Edinburgh HQ building, [the Architects' Journal, 30 November 1995, pp.29-39], the new Leeds City Office Park building [the Architects' Journal, 6 April 1994, pp.19-21], and the Barclaycard HQ building [the Architects' Journal, 1 December 1994, pp.24-25], the stereotypes for the form of an office building could be represented by the four examples described below (See Figure 4.7):

(a) Deep and Compact, low aspect ratio

- This form may find reduced size of sealed windows (small 'vision-slit' windows).
- Its internal spaces adjacent to the external walls can be daylit, but its central area, which has no external walls, requires the use of artificial lighting.
- It may be intended to control the indoor environment within narrow limits: interior spaces require careful servicing and may need comfort cooling as well as mechanical ventilation; required illuminance levels are achieved by the use of artificial lighting in interior spaces.

(b) Long and thin form

- This form can have a shallow plan.
- It can allow the use of daylight and natural ventilation (cross ventilation).
- If the office floor is fully daylit, its depth should be up to 6m. The room depth could be up to 12m if it has windows on more than 2 walls.
- The window areas on south, east and west facing walls may require solar shading devices.
- Artificial lighting can be used to supplement the daylight during the daytime and at night.
- This could have an atrium on one long side.

(c) Atrium form

- Atria can act as lightwells which allow daylight to penetrate into the bulk of a building.
- 15 m floor depth or narrow plan (12m-wide floor plates) to be fully daylit.
- Solar control devices such as blinds and sunscreen may need to be fitted;
- Artificial lighting with control may be essential.

(d) Doughnut form (courtyard)

- Courtyards can also provide the access to daylight and view to more part of the building.
- The taller the building is, however, the less such an effect will be on the lower level.
- Courtyard can also provide access to cross ventilation.
- The courtyard can be glazed to provide an atrium space.

(3) Examples of a stereotype with particular reference to daylighting design

The selected stereotype can become the starting point of the building design which could inspire creative design solutions. The stereotype may be modified taking account of the brief, such as the client's special requirements and site conditions.

Meanwhile, it is considered, as described in Section 4.2, that building design comprises a set of design issues. Taking account of the implication regarding our concern for lighting and daylighting design, the internal spaces within the building come under consideration as the design process progresses. The idea of the stereotype can be extended to consider the range of space type that might exist within the building. The idea of 'space form' or 'cell', which can represent a room or a part of the internal spaces, may be introduced, and such 'space forms' are the stereotypes for internal spaces. The 'space forms' with regard to daylighting and lighting design may be exemplified by four cells shown in Figure 4.8 (a)-(d))and their variations (e.g. combination with rooflights), as follows:

(a) <u>cell with no window or windows for provision of view</u>:

Permanent use of artificial lighting is required. Mechanical ventilation or air-conditioning needs to be considered.

(b) <u>cell with windows on one side wall, under 6m in depth (shallow plan)</u>:

This example allows sufficient daylight penetration if there is minimal external obstruction to daylight and windows can have sufficient height. It is also advantageous for natural ventilation. Some solar controls such as shading devices are necessary to avoid excess solar gain and glare for some orientations.

(c) <u>cell with windows on one side wall, over 6m in depth (deep plan)</u>:

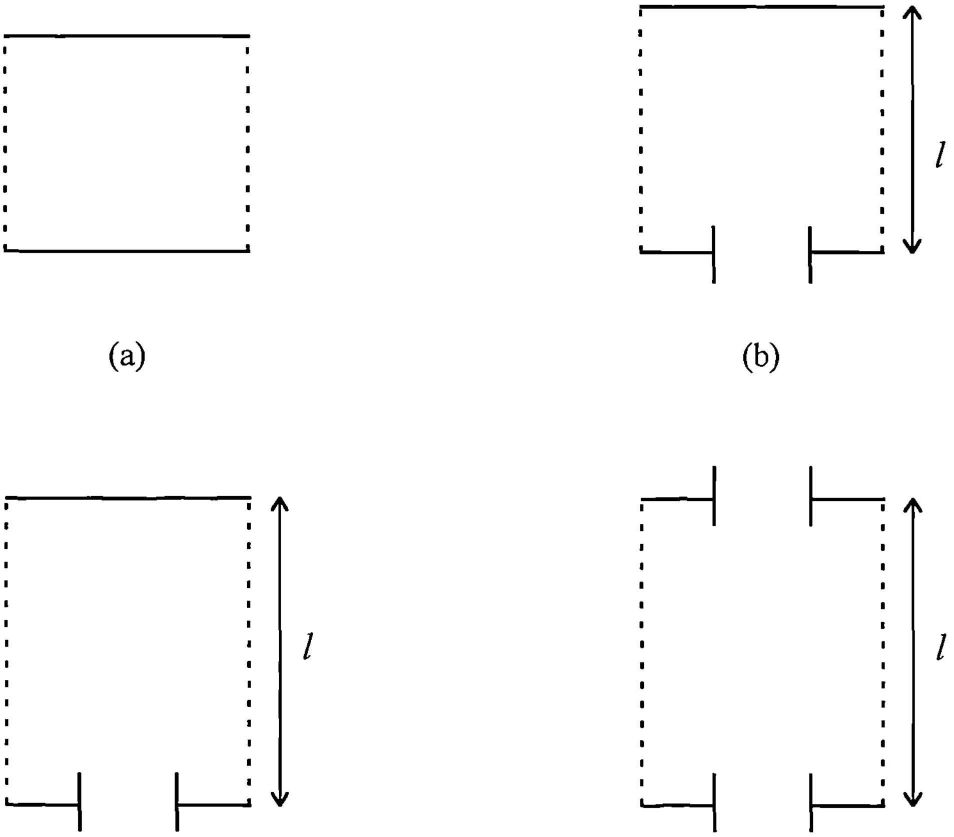
This may not be able to provide sufficient daylight distribution for the entire depth of the room unless a rooflight is fitted. Permanent artificial lighting will be required at the end of the room furthest from the window. Use of lighting control should be considered.

(d) <u>cell with windows on more than two side walls, the depth within 12m</u>

Open plan with cross-sections of depth less than 12m with windows in both walls. This can exist for narrow plan buildings or for those with courtyards. Conditions and considerations will be similar to those for (a). The number of storeys will be on important consideration for daylight penetration in facades adjacent to the courtyard, if the building is high in particular.

(e) each of these space type may have rooflights

All of these basic space forms, or cells, may be found for buildings utilising glazed spaces such as atria or glazed courtyards.



(a) (b) (c) (d)

Figure 4.8 Examples of 'space forms', or 'cells', of office floor concerning lighting and daylighting design

4.3.2 *Design variables*

A framework of building design working and a checklist embody a logical sequence of vital decision-making steps, with cross-references between the decisions in terms of the disciplines involved in the design process. To develop this framework, it was decided to describe the building design process in terms of the *design variables* associated with the *design tasks* and the relationships between them, based upon the rational description of the building design work, i.e. the hierarchy of *design issues* and *design tasks*. The building design process was studied in terms of such a framework, so as to:

(i) establish an adequate sequence of decision-making;

(ii) clarify the essential criteria relating to particular decisions; and

(iii) identify potential conflicts, particularly global ones, which might require modifications to previous decisions to resolve them.

Design variables have two properties. Firstly, they are regarded as the parameters which constitute the spaces of the 3-space model (see Figures 3.6 and 3.7 in Chapter 3). According to the 3-space conceptual model, three kinds of *design variables* can be defined as follows:

(a) *Information variables*

These relate to the design activities of obtaining and analysing information, and represent facts and data acquired from clients, e.g. the use of the building, activities carried out within the building, and also the examination of possible sites and consulting regulations. For example, site conditions such as the potential shading effects of other buildings around the site are an important consideration.

(b) *Design decision variables*

Parameters of this kind are those elements used to describe the artefact to be designed, i.e. a building, and are the objects of the design decision-making process. As the building design proceeds, design decisions are made with regard to these parameters.

(c) *Performance variables*

These represent the performance requirements as well as the performance characteristics of the designs which are evaluated in terms of these requirements.

Secondly, the *design variables* are also considered to represent the outcomes of the individual design activities, defined as the *design tasks* of the rational description of the building design work. In other words, one function of the *design tasks* is to establish particular values for these variables, in terms of *information*, *design decision*, and *performance*. Here, the *information variables* and *design decision variables* are defined in accordance with the *design tasks* specified in the previous section. The *performance variables* are, meanwhile, determined from the requirements of the brief and regulations, and will play a key role in the evaluation activities occurring during the design process.

(1) *Information variables*

The *information variables* (In) describe requirements and constraints. The information includes the client's requirements and context of the scheme. Here, the *information variables* In_01 to In_08 represent the information variables associated with the design tasks within *design issue* (1) '*General outline of requirements*', whereas In_09 to In_16 are related to *design issue* (3) '*Context of the scheme*', especially site conditions. The information regarding these *design issues* and *design tasks* can be found in Section 4.2.2 (2) 'Defining the *design issues* and *design tasks*'. These *information variables* are shown in Table 4.3 in relation to the associated design issues.

Table 4.3 *Information variables*, and the *design issues* which the variables are associated with.

Information variables		*Design issues*
In_01	Aim of the project	*Design issue* (1) General outline of requirements
In_02	Budget	
In_03	Time table	
In_04	Use of the building	
In_05	Accommodation	
In_06	Activities carried out	
In_07	Visual tasks	
In_08	Occupation patterns	
In_09	Boundaries	*Design issue* (3) Context of the scheme
In_10	Daylight availability	
In_11	Sunlight duration	
In_12	View	
In_13	Noise sources	
In_14	Physical pollution	
In_15	Ambient climate	
In_16	Local authorities and statutory regulations	

(2) *Design decision variables*

The following *design decision variables* (Dd) were identified as representing the *design tasks* in relation to the *design issues.* The *design decision variables* associated with *design issue* (6) '*Design approach/priorities*' are:

Dd_01 Daylight priorities
Dd_02 Sunshine priorities
Dd_03 View priorities
Dd_04 Ventilation priorities
Dd_05 Noise insulation priorities

The *design decision variables* associated with *design issue* (7) '*Building's arrangement on the site*':

Dd_06 Position of the building on the site
Dd_07 Orientation of the building

The *design decision variables* associated with *design issue* (8) '*Building form*':

Dd_08 Form of the building
Dd_09 Use of rooflights
Dd_10 Roof shape
Dd_11 Glazing orientation and related glazing area
Dd_12 Construction type

The *design decision variables* associated with *design issue* (9) '*Internal layout*':

Dd_13 Functional connections
Dd 14 Accommodation plan
Dd_15 Room depth

The *design decision variables* associated with *design issue* (10) '*Main ventilation methods*':

Dd_16 Use of natural ventilation
Dd_17 Need for mechanical ventilation or air-conditioning

The *design decision variables* associated with *design issue* (11) '*Window design/fenestration*':

Dd_18 Rooflight profiles
Dd_19 Glazing materials for rooflights
Dd_20 Glazed area for rooflights
Dd_21 Number and position of rooflights
Dd_22 Area and dimension of individual rooflight
Dd_23 Primary function of side windows
Dd_24 Glazing material for side windows
Dd_25 Glazed area for side windows
Dd_26 Window shapes and positions
Dd_27 Shading devices
Dd_28 Reflectance of the interior

The *design decision variables* associated with *design issue* (12) '*Artificial lighting installation*':

Dd_29 Function of artificial lighting
Dd_30 Lighting system
Dd_31 Lamp types
Dd_32 Lighting luminaires
Dd_33 Arrangement of the luminaires
Dd_34 Lighting control system

These *design decision variables* are summarised in Table 4.4 with the associated *design issues*.

Table 4.4 *Design decision variables* and their associated *design issues* (1/2).

Design issues	*Design decision variables*	
Design issue (6) Design approach / priorities	Dd_01	Daylight priorities
	Dd_02	Sunshine priorities
	Dd_03	View priorities
	Dd_04	Ventilation priorities
	Dd_05	Noise insulation priorities
Design issue (7) Building's arrangement on the site	Dd_06	Position of the building on the site
	Dd_07	Orientation of the building
Design issue (8) Building form	Dd_08	Form of the building
	Dd_09	Use of rooflights
	Dd_10	Roof shape
	Dd_11	Glazing orientation and related glazing area
	Dd_12	Construction type
Design issue (9) Internal layout	Dd_13	Functional connections
	Dd_14	Accommodation plan
	Dd_15	Room depth
Design issue (10) Main ventilation methods	Dd_16	Use of natural ventilation
	Dd_17	Need for mechanical ventilation or air-conditioning

Table 4.4 (continued) *Design decision variables* and their associated *design issues* (2/2).

Design issues	*Design decision variables*
Design issue (11) Window design / fenestration	Dd_18 Rooflight profiles Dd_19 Glazing materials for rooflights Dd_20 Glazed area for rooflights Dd_21 Number and position of rooflights Dd_22 Area and dimension of individual rooflight Dd_23 Primary function of side windows Dd_24 Glazing material for side windows Dd_25 Glazed area for side windows Dd_26 Window shapes and positions Dd_27 Shading devices Dd_28 Reflectance of the interior
Design issue (12) Artificial lighting installation	Dd_29 Function of artificial lighting Dd_30 Lighting system Dd_31 Lamp types Dd_32 Lighting luminaires Dd_33 Arrangement of the luminaires Dd_34 Lighting control system

(3) *Design aspects* and *performance variables*

Both *design aspects* and *performance variables* are associated with the performance characteristics of the building to be, or being, designed.

(a) *Design aspects*

The building performance consideration may be one of the most discipline-specific activities of the building design process, because there are various perspectives from which the characteristics of the artefact should be considered, including those of "*energy consumption*" and "*visual environment*" (Figure 4.9). Such perspectives may be called "*design aspects*". These *design aspects* often help to define the broad requirements, or design objectives, of the building to be designed with regard to its performance (Figure 4.10 (a)). However, within these aspects, a need often arises to pay particular attention to elements which correspond to the expertise of a single profession involved in a building design project.

Each of the *design aspects* may be a category within the predictive capability of one or more discipline-specific building simulation programs (see Figure 4.7). The developed framework may, therefore, be able to provide a structure that in the long term, could combine and enhance the use of the back-end capability of these design tools, as well as making relevant design expertise available from computer data bases, during the course of the building design process. To develop such a framework for inter-disciplinary building design working relating to the confines of daylighting and lighting, it was decided to identify the relevant *design aspects.* Eventually, by considering the internal and external environments, as well as the energy efficient performance of a building, and taking account of the functions of a building as discussed in Chapter 1 (see Section 1.2.2 "*What is a building?*"), the following were specified for this project:

Da_0 *Energy efficiency*

This concerns factors affecting the energy consumption of the building, such as *heat loss* and the *efficiency and utilisation of lighting equipment*;

Da_1 *Thermal comfort*

covers those issues relating to thermal comfort of occupants within the building, e.g. *solar gain* in summer, in relation to window design;

Da_2 *Air quality*

handles ventilation aspects, in relation to the ambient environment and fenestration in particular, in terms of natural ventilation;

Da_3 *Visual environment (lighting)*

This involves a wide range of illumination-related issues, such as *illuminance*, *uniformity*, *glare* and *colour properties*;

Da_4 *Visual environment (view)*

deals with the view from windows in relation to fenestration;

Da_5 *Acoustic consideration (noise)*

from which noise insulation and potential noise from open windows are considered;

Da_6 *Structural consideration*

is mainly concerned with structural aspects of the building, particularly in terms of fenestration;

Da_7 *External environment*

involves the external environment surrounding the building, such as overshadowing, and ambient air quality;

Da_8 *Cost*

This includes both the *initial cost* of the design and the *running costs* of its building services systems; and

Da_9 *Aesthetics*

This is concerned with the appearance of the building itself, as well as the environment created in relation to the building. It is a subjective matter, and tends to depend upon the client's preference, the designer's philosophy and the trends existing at the time when it is built.

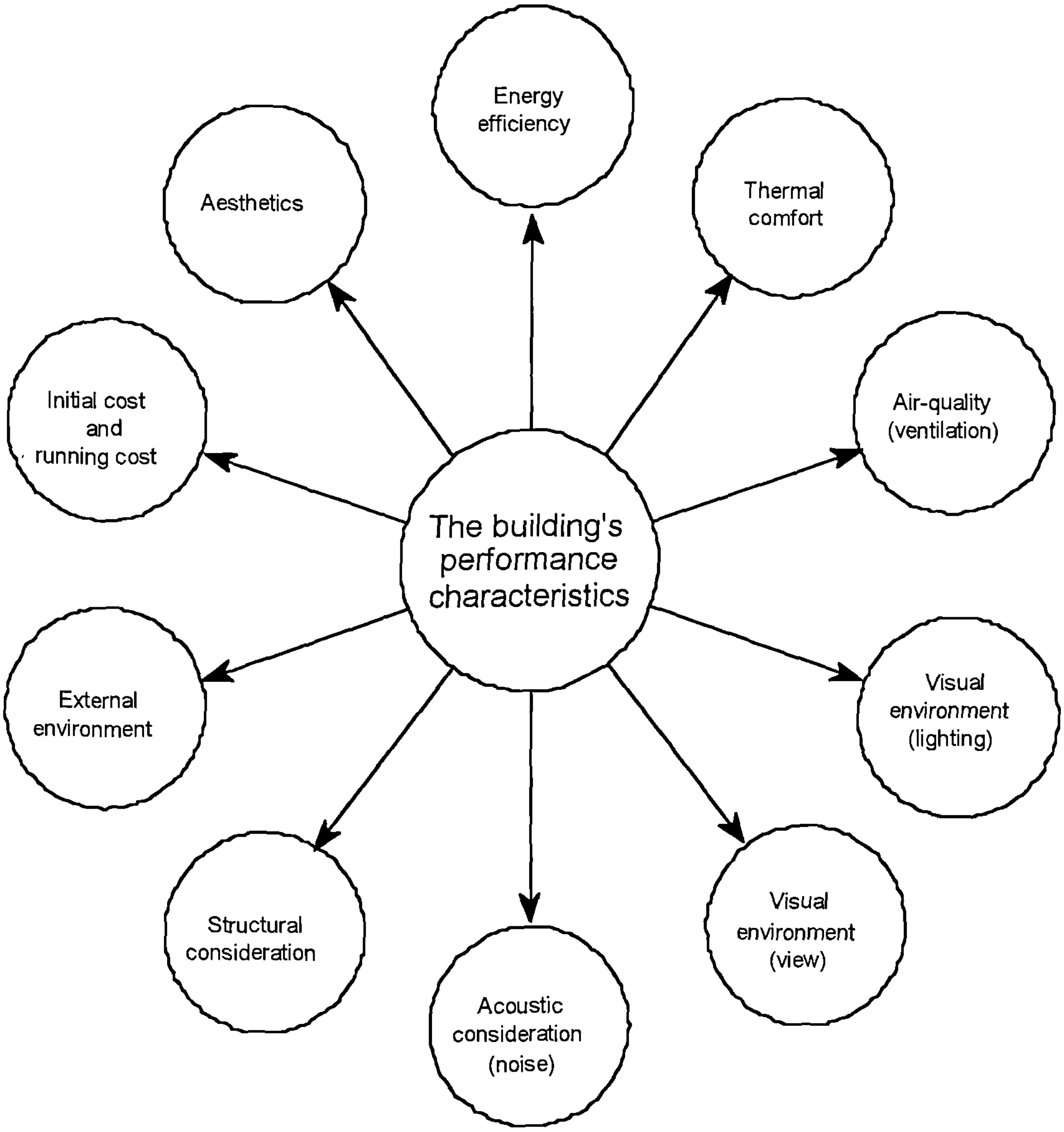


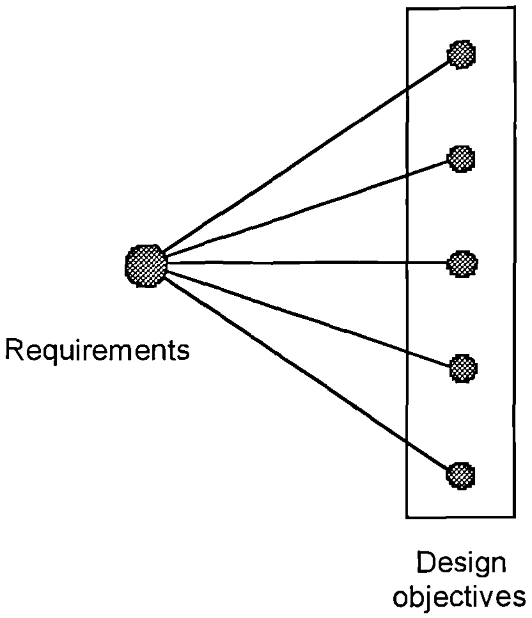
Figure 4.9 *Design aspects*, representing the performance characteristics of a building

(b) *Performance variables*

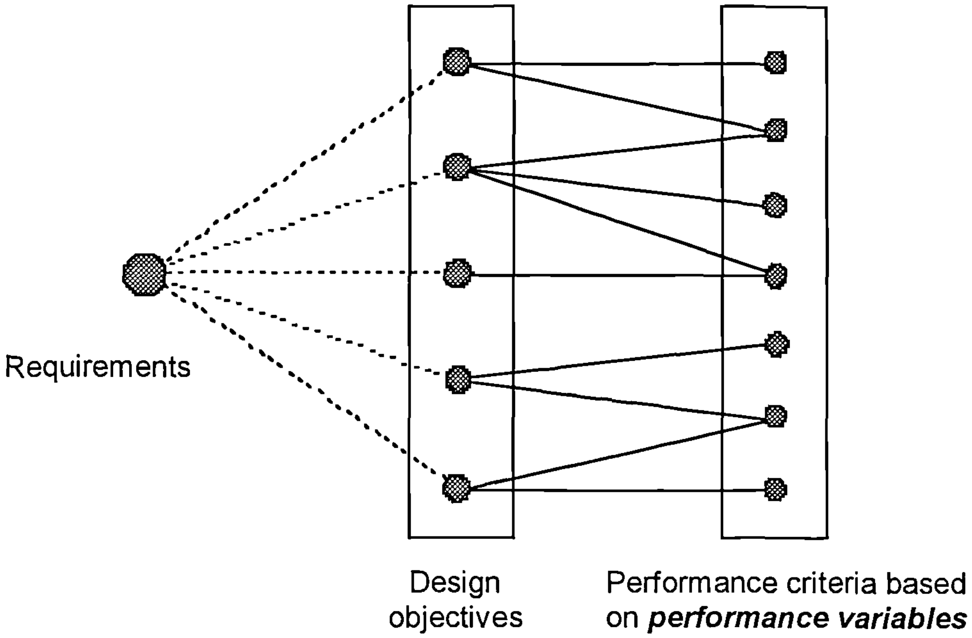
The function of the *performance variables* is to describe the required performance characteristics of a building in detail (Figure 4.10 (b), whereas the *design aspects* are considered to represent them more broadly (see Figure 4.10 (a)). This function has two elements.

Firstly, the *performance variables* describe the predicted performance characteristics of the building being designed to allow the evaluation of a particular design idea or option, and eventually constitute the *performance space* of the 3-space model (Figure 4.11). Let us describe the *performance variables* as "**Pe**" (*performance variables for evaluation*). The *performance variables, Pe,* may be defined in association with the *design aspects,* which represent the perspectives of the building's performance. In this sense, their values may not be singular but rather groups of inter-dependent parameters which have relationships both within and across the *design aspect* categories.

Secondly, the *performance variables* are considered as the parameters upon which *performance criteria* are established. The *performance criteria,* which may be designated with the symbol "**Pc**", describe the bounding limits of the *performance variables,* or the numerical values of design targets. Within the early stages of the design process, having identified the design objectives in terms of the *design aspects* (see Figure 4.10 (a)), the *performance criteria* are established in terms of *performance variables,* developed from information sources, such as the client's requirements and Building Regulations, and design team knowledge (see Figure 4.10 (b)). The *performance criteria* (Pc) are related to the *design tasks* contained within the *design issues* (2) '*Design objectives*' and (5) '*Performance criteria*' (see Table 4.4). In this context, some, if not all, of the *performance variables for evaluation* (Pe) are associated with the *performance criteria* (Pc), and any evaluation of a proposed design solution may involve comparisons between Pe and Pc (see Figure 4.11).



(a) Establishing broad requirements, or design objectives, in terms of the *design aspects*



(b) Establishing the performance criteria, which define the limits on the *performance variables*, in relation to the design objectives.

Figure 4.10 Establishing design objectives and performance

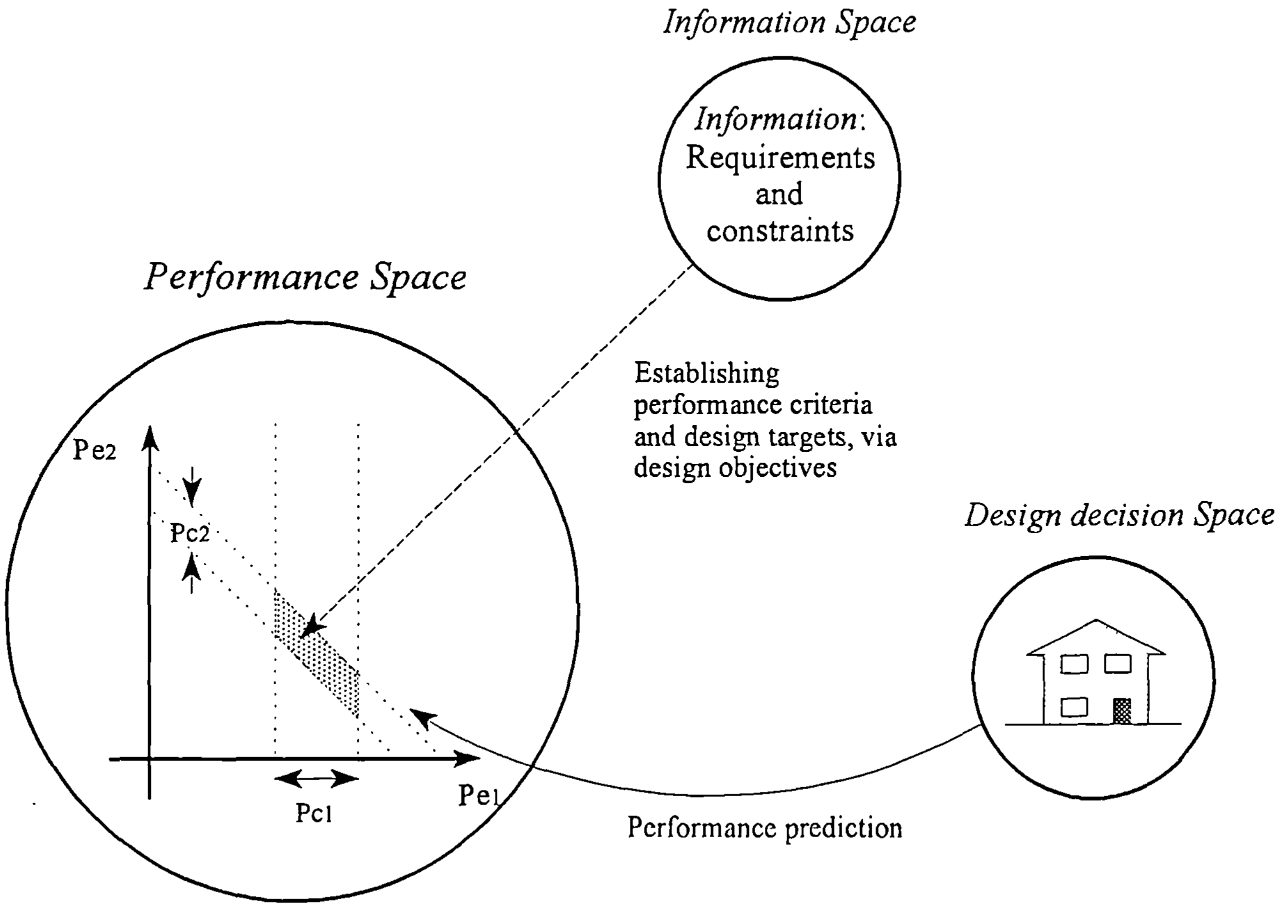


Figure 4.11 Two features of the *performance variables*: representing the performance characteristics of a building (Pe), and describing the design criteria, or constraints, regarding the performance characteristics (Pc).
Pe1 and Pe2: *performance variables* to represent the estimated allowable range of the performance characteristics;
Pc1 and Pc2: *performance criteria* corresponding to Pe1 and Pe2, respectively.

Having studied the building design process in terms of the various *design aspects,* as well as considering the evaluation activities involved in the development of the design with particular reference to daylighting and lighting design aspects, the following *performance variables* were defined for this project. These *performance variables* are shown in Table 4.5 in relation to the *design aspects.*

Table 4.5 *Performance variables* representing the performance characteristics of a design option, and their associated *performance criteria*, in relation to the *design aspects*

Design aspects	**"Pe"**: *performance variables* representing the performance characteristics of a design option	**"Pc"**: *performance criteria* associated with the *performance variables*
Da_0 *Energy efficiency*	Pe_01 Energy consumption	Pc_01 Energy targets
	Pe_02 Heat loss	none
Da_1 *Thermal comfort*	Pe_03 Solar gain	Pc_03 Thermal comfort level required
Da_2 *Air quality*	Pe_04 Ventilation performance	Pc_04 Air qualities required
Da_3 *Visual environment* *(lighting)*	Pe_05 Illuminance level on a working plane	Pc_05 Illuminance level required
	Pe_06 Uniformity of illuminance level	Pc_06 Uniformity required
	Pe_07 Average daylight factor (ADF)	Pc_07 Target ADF
	Pe_08 Colour properties	Pc_08 Colour properties required
	Pe_09 Appearance / modelling	none
	Pe_10 Glare and specular reflection	none
Da_4 *Visual environment (view)*	Pe_11 View	none
	Pe_12 Privacy	none
Da_5 *Acoustic consideration*	Pe_13 Noise level within the building	Pc_13 Noise insulation level required
Da_6 *Structural consideration*	Pe_14 Structure	none
Da_7 *External environment*	Pe_15 Overshadowing	none
Da_8 *Cost*	Pe_16 Cost	Pc_16 Cost range criteria (construction)
Da_9 *Aesthetics*	Pe_17 Aesthetics	none

4.3.3 The relationships between the *design variables*

As pointed out in Section 4.3.2, the *design variables* can be considered as the parameters which constitute the spaces of the 3-space conceptual model, i.e. *information*, *design decision*, and *performance* spaces. The *design tasks* are considered to establish particular values for the associated *design variables*, in relation to other *design variables* or the outside information such as the client's requirements and site constraints. Considering the establishment of the values for *design variables*, the design activities can be categorised into the following 5 types, in relation to the mapping between the spaces described within the 3-space model (Figure 4.12).

(a) Acquiring the necessary information

Information regarding the client's requirements and site conditions is obtained through initial design activities, such as meetings with the client and examining the site. The *information variables* describe the requirements and constraints applied to the project (see Figure 4.12 (a)). This activity involves the *design tasks* originating from *design issues* (1) '*General outline of requirements*' and (3) '*Context of the scheme*', which are undertaken at the beginning of the building design process.

(b) Setting up design objectives and establishing performance criteria

This activity is represented by the mapping of design requirements and constraints from the *information space* to the *performance space* (see Figure 4.12 (b)). Establishing the consequent performance criteria is achieved in two steps. Firstly, by analysing the information obtained which is associated with *design issues* (1) and (3), design objectives are set up in terms of the *design aspects* which help to define the broad requirements of the project (Figure 4.10 (a)). These objectives can be regarded as the interpretation of the desired states of the various performance requirements of the building. Secondly, performance criteria are established in terms of the *performance variables*, such as "*illuminance level required*" and "*target average daylight factor*", so as to achieve the design objectives (Figure 4.10 (b)). The desired performance states may be called "*design targets*". When establishing the *design targets*, existing technological and financial constraints have to be taken into account. Figure 4.11 illustrates that performance criteria (Pc), which define the performance limits, are eventually established, in terms of the *performance variables*

(Pe), in relation to information including the client's requirements and various constraints. The *design tasks* belonging to *design issues* (2) '*Design objectives*' are associated with setting up design objectives, and those originating from (4) '*Feasibility study*' and (5) '*Performance criteria*', are undertaken to establish the performance criteria.

(c) Ensuring physical and functional constraints

This can be described as the mapping from the *information space* to the *design decision space* (see Figure 4.12 (c)). The *design tasks* of *design issues* (3) '*Context of the scheme*' and (6) '*Design approach*' can be associated with this type of activity. Here, possible descriptions of a building are often constrained physically and/or functionally depending upon the client's requirements as well as particular site conditions. As a result, some of the *design decision variables* may have certain limits on their values.

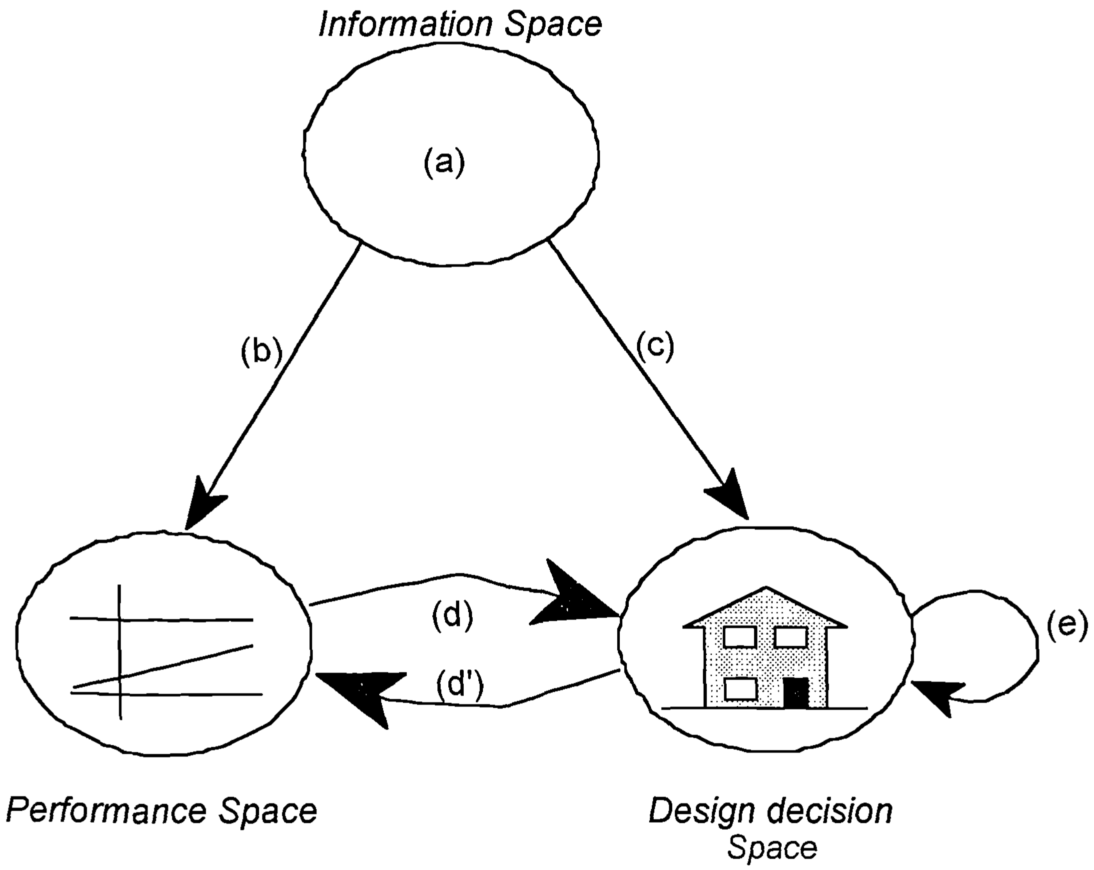
(d) Developing a design, considering its performance

This is represented by the mapping between the *performance space* and *design decision space* (see Figure 4.12 (d) and (d')). Most of the *design tasks* within *design issues* (7)-(12) (see Section 4.2), involve this type of activity. Having established performance criteria (design targets) and the design approach, design proposals may be developed by determining particular values for the *design decision variables* (Figure 4.12 (d)). The performance characteristics of the proposals are then evaluated (Figure 4.12 (d')). In other words, the design proposals are examined in terms of the *performance variables*, Pe, and the *performance criteria*, Pc (see Figure 4.11). The results of this examination may well be used to refine the design proposals (Figure 4.12 (d)). These activities may, therefore, be described in terms of the relationships between the *performance variables* and *design decision variables* (Figure 4.13).

(e) Developing a design considering preceding design decisions

This is described as the mapping from the *design decision space* onto itself (Figure 4.12 (e)). This type of mapping may be described in terms of the relationships between the *design decision variables* themselves. This implies that some design decisions may need to be made based upon those which have already been made, since they may be restricted physically or functionally by the preceding design decisions. For instance, design decisions related to '*Artificial lighting installation*' are likely to be affected by those associated with '*Window design*'. During the processing of *design tasks* originating from *design issues* (7) onwards, such relationships need to be considered because they may well cause conflicts between chosen design solutions. The more the process progresses the more likely it is that such conflicts will appear, as the design becomes more specified and concrete.

All the types of design activities except Type (a) "acquiring the necessary information", involve the mapping between the three spaces, which can be described in terms of the relationships between the *design variables*, i.e. the relationships between the *information* and *performance variables*; the *information* and *design decision variables*; the *performance* and *design decision variables*, and those between the *design decision variables* themselves (Figure 4.14). This rationalisation should allow design criteria and potential conflicts to be identified by examining the relationships between the *design variables.* The relationships between the *design decision variables* in particular may greatly affect the favourable sequence of design decision-making steps. This aspect has been studied using graph theory and is described in detail in Appendix F.



(a) Acquiring *information*:
Collecting information such as the client's requirements and site conditions.

(b) Mapping from *Information* to *Performance*:
Establishing design objectives, and, eventually, performance criteria (design targets) by analysing the requirements and constraints.

(c) Mapping from *Information* to *Design decision* Defining physical and functional constraints based upon the information.

(d) Mapping from *Performance* to *Design decision*:
Developing design solutions considering the design targets and the evaluation of results.

(d') Mapping from *Design decision* to *Performance*:
Predicting and evaluating the performance characteristics of the proposed design solutions.

(e) Mapping from *Design decision* to itself:
Considering the design decisions already made which may constrain subsequent design decisions.

Figure 4.12 The design activities and the mapping between the spaces

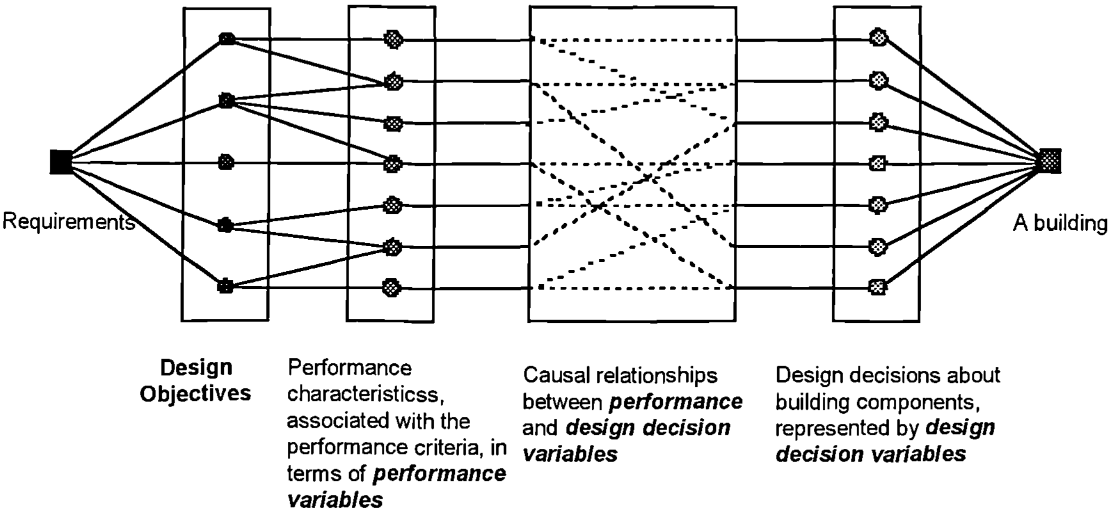


Figure 4.13 Developing a design solution, considering its performance: the relationships between ***performance*** and ***design decision variables***.

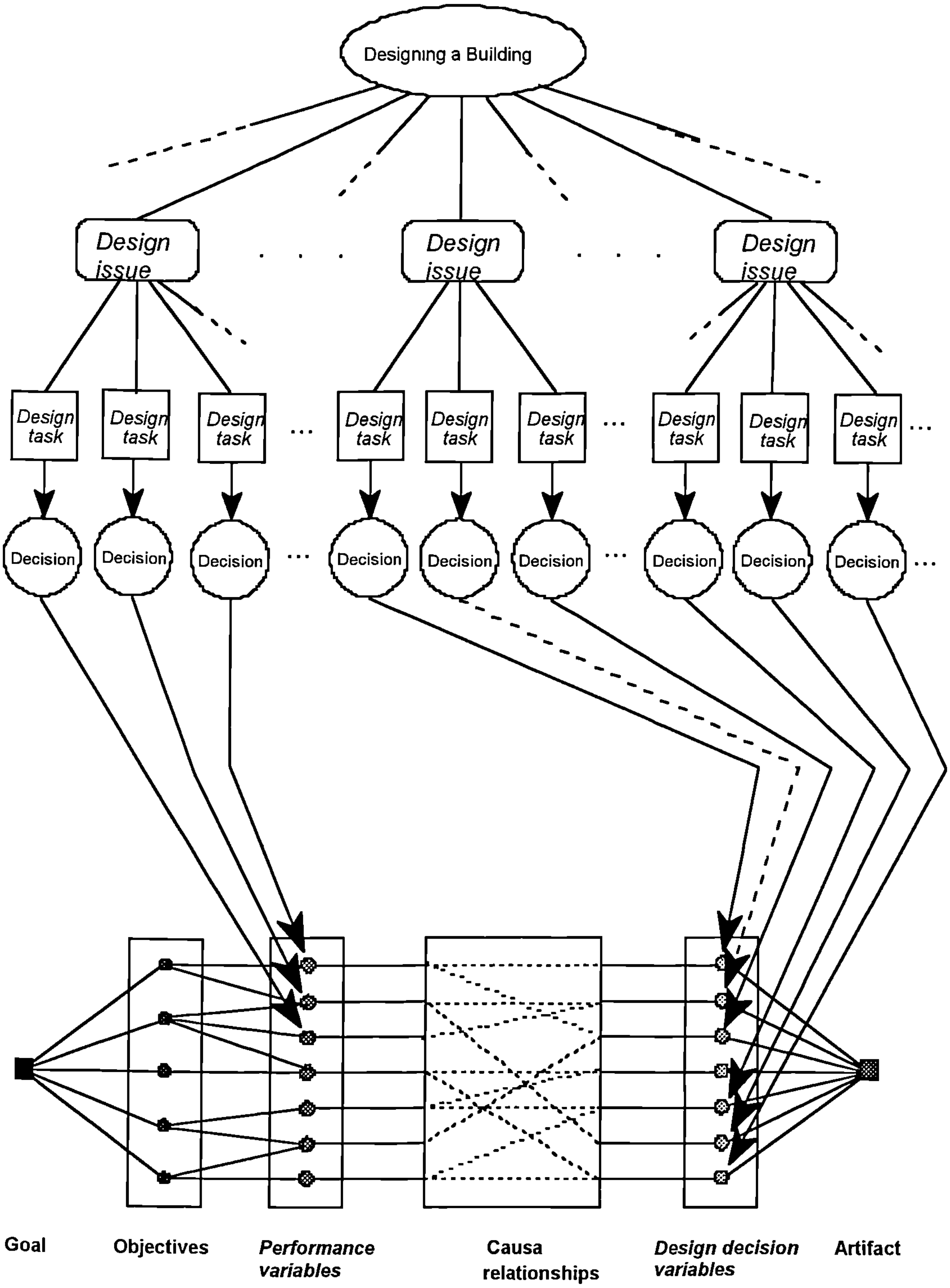


Figure 4.14 Design tasks related to the design variables, and the relationships between them: *Design tasks* are the individual processes which establish values of the design variables taking account of their inter relationships.

4.3.4 Approach to develop a framework for inter-disciplinary design working

In order to develop a framework for inter-disciplinary design working, it was decided to seek the expertise which explains the relationships between *design variables* based upon published materials. This expertise was itemised as units of knowledge, and used to identify the relationships. Associated with the relevant knowledge units, the identified relationships were also described in a matrix form. The relationships between the *design variables* were further examined based upon the matrix representation, so that a logical sequence of design decision-making steps, as well as the cross-references between the *design variables*, were developed.

(1) The relationships between *design variables* and expertise

Having defined the *design variables*, the building design process was studied with particular reference to daylighting and lighting design aspects, in terms of the relationships between them. Although they are not always obvious, it was considered that the relationships between the *design variables* should be embodied, either explicitly or implicitly, within the design methodologies which have been established through experience and/or described within the publications which aim to provide 'good practices' concerning particular design issues. In other words, well-established individual design processes which set particular values for the *design variables*, may imply the existence of other *design variables*, although these may not be described overtly or systematically (see Figure 4.12). It was, therefore, decided to identify the relationships between the *design variables* by using available published materials, which appear to be widely accepted among designers. These include:

- BS8206 *Lighting for Buildings, Part 1 Code of practice for artificial lighting* [1985]
- BS8206 *Lighting for Buildings, Part 2 Code of practice for daylighting* [1992]
- BS8207 *Code for Energy Efficiency in Buildings* [1985]
- CIBSE 'Application Manual *Window Design*' [1987]
- CIBSE *Code for Interior Lighting* [1984]
- Esmond Reid, *Understanding Buildings*, Longman Scientific & Technical [1984].

Some of the units may refer to Appendix B, where lighting design methodologies are explained.

(2) Itemised knowledge units

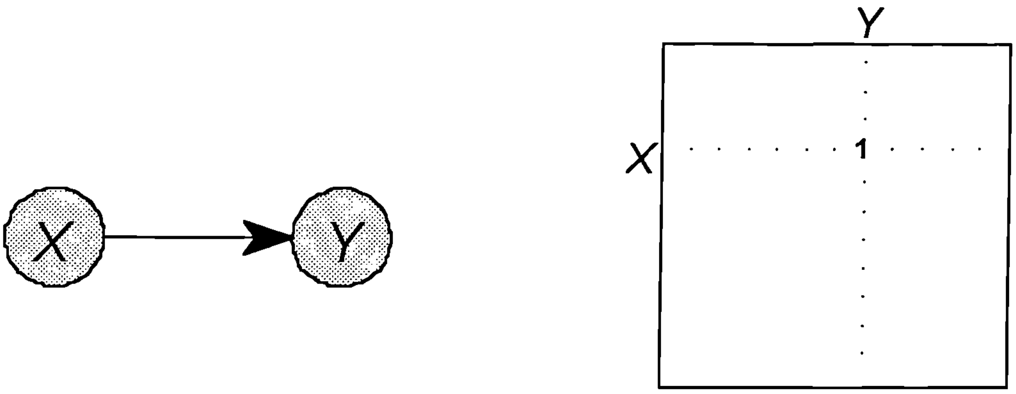
The expertise described within the written materials was extracted and itemised as units of knowledge. Each of these units is regarded as an item of expertise which can be associated with one or several *design variables.* These itemised knowledge units are presented in Appendix D. Each unit of knowledge has a reference number that consists of an abbreviation of the source and a number (e.g. AM[23]; "AM" stands for the CIBSE 'Application Manual *Window Design*'. As for the abbreviations, see Appendix D). The reference numbers are used to specify the itemised knowledge units related to a particular relationship between *design variables.* These itemised knowledge units will be the information source for the intelligent knowledge-based system to be described in Chapter 6, as well as the checklist for inter-disciplinary building design working.

4.3.5 Matrix representation of the relationships and the reference directory

The relationships between particular pairs of *design variables* were identified in terms of the units of knowledge extracted from the published materials. In other words, the design activities were studied based upon the units of knowledge, considering these combinations of the *design variables.* The results were initially represented in matrix forms which describe the existence of the relationship between a particular pair of *design variables.* Subsequently, a *reference directory* was developed which allows the units of knowledge to be accessed through these matrices. The matrix representation and the development of the reference directory are explained below.

(1) The matrix representation of the relationships

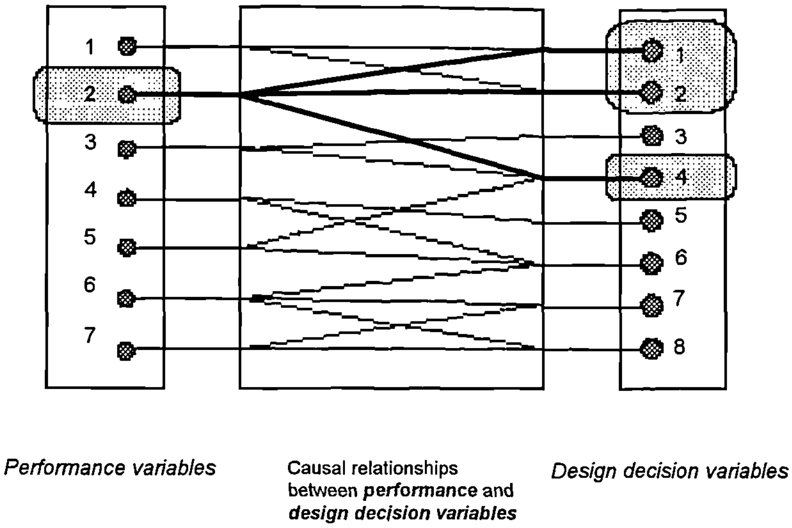
The existence of the relationships between the *design variables* was represented by binary matrices, where each element of the matrices will have a value of "1" if any units of knowledge can be associated with the relationship between its corresponding pair of *design variables*, otherwise it has "0". Figure 4.15 exemplifies the case of the relationship between two *design decision variables*, "*X*" and "*Y*". If the design decision represented by the *design decision variable* "*X*" may affect the other decision "*Y*" (Figure 4.15 (a)), the existence of such a relationship is described by the (*X*, *Y*) element which has a value of "1" within a matrix (Figure 4.15 (b)). Figure 4.16 and Figure 4.17 show an example of a matrix representation regarding the relationships between *performance* and *design decision variables.*



(a) Design decision "*X*" may affect " *Y*".

(b) The relationship between "*X*" and "*Y*" represented in the binary *Design decision-Design decision Matrix*, M_{DdDd}.

Figure 4.15 The matrix representation of the relationship between particular *design decision variables* "*X*" and "*Y*".



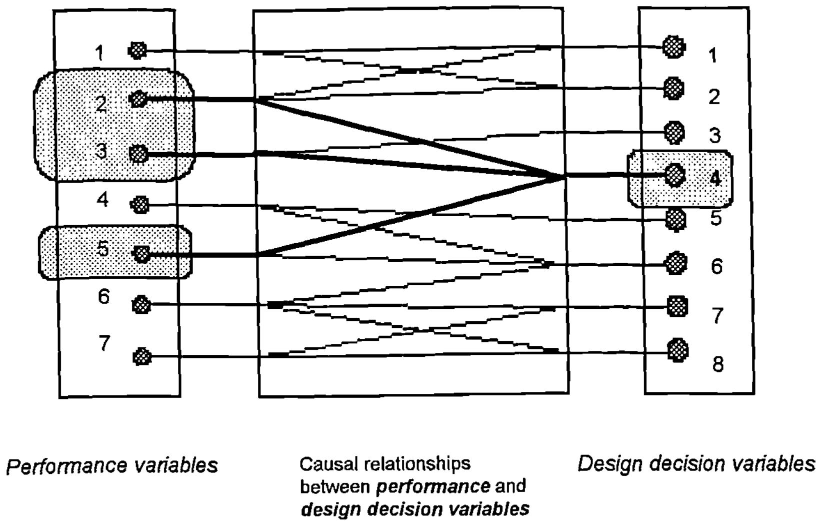
(a) The relationships between *performance* and *design decision variables*, with particular reference to the " *performance variables 2*".

Performance variables

Design decision variables	1	2	3	4	5	6	7
1	1	1	0	0	0	0	0
2	1	1	0	0	0	0	0
3	0	0	1	0	0	0	0
4	0	1	1	0	1	0	0
5	0	0	0	1	0	0	0
6	0	0	0	1	1	1	0
7	0	0	0	0	0	1	1
8	0	0	0	0	0	1	1

(b) M_{DPe} Matrix describing the relationships between *performance* and *design decision variables*, shown above.

Figure 4.16 The matrix describing the relationships between *performance* and *design decision variables* (1): conflicts might occur between the *design decision variables 1*, *2*, and *4*, with particular reference to the *performance variable 2*



(a) The relationships between *performance* and *design decision variables*, with particular reference to the '*design decision variables 4*'.

Performance variables

Design decision variables	1	2	3	4	5	6	7
1	1	1	0	0	0	0	0
2	1	1	0	0	0	0	0
3	0	0	1	0	0	0	0
4	0	1	1	0	1	0	0
5	0	0	0	1	0	0	0
6	0	0	0	1	1	1	0
7	0	0	0	0	0	1	1
8	0	0	0	0	0	1	1

(b) M*DPe* Matrix describing the relationships between *performance* and *design decision variables*, shown above.

Figure 4.17 The matrix describing the relationships between *performance* and *design decision variables* (2):'*performance variable 2*', '3' and '5'" are the design criteria for '*design decision variable 4*'.

Corresponding to the mapping between the three spaces described in Figure 4.12, the relationships between the *design variables* were described in terms of four combinations of the *design variables*, i.e.

(a) *information* and *performance*,
(b) *information* and *design decision*,
(c) *performance* and *design decision*, and
(d) *design decision* and *design decision*.

In accordance with the four combinations, the following matrices were developed:

(a) **Information-Performance Matrix, "M_{InPe}"** (Table 4.6), and **Information-Performance criteria Matrix, "M_{InPc}"** (Table 4.7)

These matrices associate the *information variables* with the *performance variables* and the *performance criteria* (see also Figure 4.12 (b)):

M_{InPe} describes the relationships between the *performance variables* and the information required during the evaluation process (Table 4.6), and

M_{InPc} concerns establishing the design objectives and design targets, i.e. establishing *performance criteria* (Pc) based upon the relevant information (Table 4.7).

(b) **Information-Design decision Matrix, "M_{InDd}"** (Table 4.8)

Relating the *information variables* to the *design decision variables*, this matrix describes the likelihood that some information items impose physical or functional constraints on design decisions (see also Figure 4.12 (c)).

(c) **Design Decision-Performance Matrix, "M_{DdPe}"** (Table 4.9)

This matrix is associated with the relationships between the *design decision* and *performance variables* (including the performance criteria), to deal with the development of a design idea in terms of both the synthesis and evaluation of a design proposal (see also Figure 4.12 (d) and (d')).

(d) **Design Decision-Design Decision Matrix, "M_{DdDd}"** (Table 4.10)

This combines *design decision variables* and describes constraints imposed by preceding design decisions, i.e. the dependencies between the design decisions. This matrix is concerned with the effects of earlier decisions on later decisions made as the design procedure progresses (see also Figure 4.12 (e)).

These matrices indicate whether or not any relationships exist between particular *design variables*, but do not say what these relationships are.

Table 4.6 M_{InPe}: Matrix representing the relationships between *information variables* (In) and *performance variables* (Pe)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Pe01	Pe02	Pe03	Pe04	Pe05	Pe06	Pe07	Pe08	Pe09	Pe10	Pe11	Pe12	Pe13	Pe14	Pe15	Pe16	Pe17
1	In_01																	
2	In_02																	
3	In_03																	
4	In_04	1																
5	In_05							1										
6	In_06	1									1							
7	In_07																	
8	In_08	1																
9	In_09												1			1		
10	In_10		1	1				1								1		
11	In_11		1	1														
12	In_12											1						
13	In_13													1				
14	In_14																	
15	In_15	1	1															
16	In_16																	

Table 4.7 M_{InPc}: Matrix representing the relationships between *information variables* (In) and *performance criteria* (Pc)

		1	2	3	4	5	6	7	8	9
		Pc01	Pc03	Pc04	Pc05	Pc06	Pc07	Pc08	Pc13	Pc16
1	In_01	1								
2	In_02	1								1
3	In_03									
4	In_04									
5	In_05						1			
6	In_06		1	1	1	1		1	1	
7	In_07				1	1		1		
8	In_08						1			
9	In_09									
10	In_10						1			
11	In_11									
12	In_12									
13	In_13									
14	In_14									
15	In_15									
16	In_16									

Table 4.8 M_{InDd}: Matrix representing the relationships between *information variables* (In) and *design decision variables* (Dd)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		d01	d02	d03	d04	d05	d06	d07	d08	d09	d10	d11	d12	d13	d14	d15	d16	d17	d18	d19	d20	d21	d22	d23	d24	d25	d26	d27	d28	d29	d30	d31	d32	d33	d34
1	In_01	1		1	1																														
2	In_02																																		
3	In_03																																		
4	In_04		1										1																						
5	In_05													1	1																				
6	In_06	1	1	1		1						1		1					1				1			1	1				1	1	1		
7	In_07	1																			1					1					1	1			
8	In_08	1										1	1										1				1								1
9	In_09	1	1				1	1	1															1		1	1								
10	In_10	1	1				1	1	1			1				1					1	1	1	1		1	1			1					
11	In_11		1																									1							
12	In_12			1																						1	1								
13	In_13	1	1		1	1	1	1	1			1					1	1	1						1	1	1								
14	In_14	1	1	1	1		1	1	1	1		1					1	1	1		1				1	1	1								
15	In_15	1	1		1		1	1	1			1					1		1		1				1	1						1			
16	In_16						1	1	1			1									1					1									

Table 4.9 M_{DdPe}: Matrix representing the relationships between *design decision variables* (Dd) and *performance variables* (Pe)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Pe01	Pe02	Pe03	Pe04	Pe05	Pe06	Pe07	Pe08	Pe09	Pe10	Pe11	Pe12	Pe13	Pe14	Pe15	Pe16	Pe17
1	Dd_01	1	1	1			1	1	1	1	1	1						
2	Dd_02	1		1							1							
3	Dd_03											1	1					
4	Dd_04																	
5	Dd_05																	
6	Dd_06			1				1				1	1			1		
7	Dd_07			1				1				1	1			1		
8	Dd_08	1	1	1				1					1			1	1	1
9	Dd_09		1	1			1			1								
10	Dd_10			1														
11	Dd_11	1	1	1				1			1		1					
12	Dd_12	1	1															
13	Dd_13					1												
14	Dd_14			1		1		1	1	1								
15	Dd_15							1				1						
16	Dd_16	1	1															
17	Dd_17	1	1															
18	Dd_18		1	1				1		1								
19	Dd_19		1	1				1	1		1							
20	Dd_20	1	1	1				1										
21	Dd_21						1				1				1			
22	Dd_22		1	1			1	1			1							
23	Dd_23									1								1
24	Dd_24		1	1				1	1		1			1				1
25	Dd_25	1	1	1				1				1		1				1
26	Dd_26		1	1	1		1	1		1	1	1	1		1			1
27	Dd_27	1	1	1	1		1	1	1		1	1						1
28	Dd_28					1	1	1			1							1
29	Dd_29	1				1	1	1	1	1	1							
30	Dd_30	1				1	1										1	
31	Dd_31	1							1		1						1	
32	Dd_32	1									1						1	
33	Dd_33	1					1			1	1						1	
34	Dd_34	1					1										1	

Table 4.10 M_{DdDd}: Matrix representing the relationships between *design decision variables* (Dd) themselves

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		d01	d02	d03	d04	d05	d06	d07	d08	d09	d10	d11	d12	d13	d14	d15	d16	d17	d18	d19	d20	d21	d22	d23	d24	d25	d26	d27	d28	d29	d30	d31	d32	d33	d34
1	Dd_01						1	1	1	1		1			1	1					1			1		1	1	1		1					
2	Dd_02			1			1	1	1	1		1			1				1	1					1		1	1							
3	Dd_03		1					1				1												1		1	1	1							
4	Dd_04								1							1	1	1							1		1								
5	Dd_05	1	1		1							1					1	1							1	1	1								
6	Dd_06																																		
7	Dd_07											1																							
8	Dd_08						1			1	1	1							1		1			1	1	1	1			1					
9	Dd_09								1		1								1									1							
10	Dd_10																		1																
11	Dd_11																						1		1	1		1		1					
12	Dd_12																					1				1	1								
13	Dd_13														1																				
14	Dd_14															1										1									
15	Dd_15														1		1									1	1			1					
16	Dd_16																	1							1		1	1							
17	Dd_17																																		
18	Dd_18																						1					1							
19	Dd_19																				1														
20	Dd_20															1				1			1												
21	Dd_21															1							1					1			1			1	
22	Dd_22															1												1							
23	Dd_23																								1	1	1								
24	Dd_24																									1	1	1							
25	Dd_25															1									1										
26	Dd_26															1												1		1	1	1		1	
27	Dd_27																				1					1									
28	Dd_28															1					1					1				1					
29	Dd_29																														1	1		1	1
30	Dd_30																																		1
31	Dd_31																																1		1
32	Dd_32																															1			
33	Dd_33																																		1
34	Dd_34																																	1	

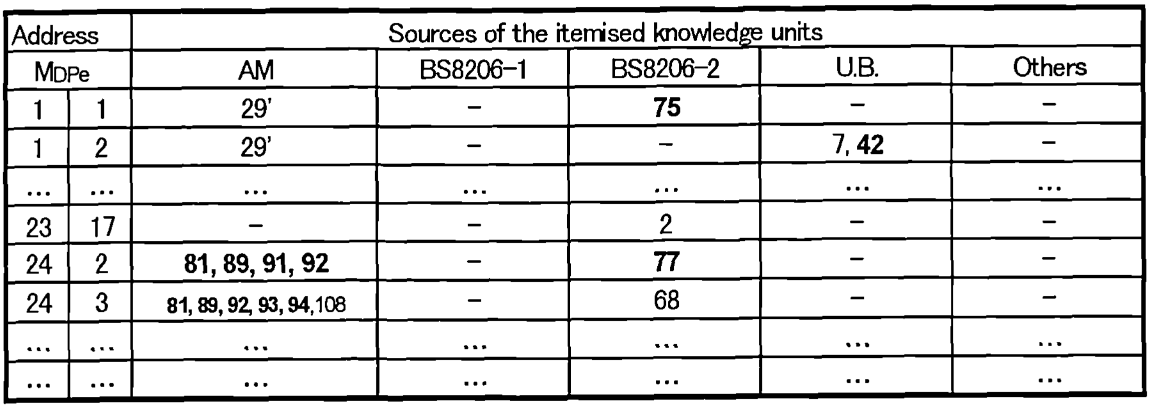
(2) Reference directory

Since the matrices indicate only the existence of the relationships between particular *design variables*, it is necessary to go back to the itemised knowledge units which describe the relationships between the *design variables*. To provide the access to the knowledge associated with particular relationships, therefore, a *reference directory* was developed in accordance with the matrix representation of the relationships between *design variables*, i.e. M_{InPe}, M_{InPc}, M_{InDd}, M_{DdPe}, M_{DdDd}, and is presented in Appendix E.2. The reference directory is a table comprising:

- the "*address*" to specify a particular relationship, and
- the "*reference numbers*" of the itemised knowledge units, described in Appendix D.

Here, the *address* comprises the name of the matrix describing the relationships between particular *design variables*, such as M_{DdPe} for those between *design decision variables* and *performance variables*, and the position of an element within the matrix which has a value of "1", so that a particular pair of *design variables* can be specified. For example, in Table E.10 of Appendix E (identical to Table 4.9 of this section), the address "$M_{DdPe}(24, 2)$" means the (24, 2) element of the matrix M_{DdPe}, which represents the relationship between the *design decision variables* "Dd_24 *Glazing material for side windows*" and the *performance variable* "Pe_2 *Heat loss*". The *reference numbers* are, meanwhile, used to specify the itemised knowledge units which are associated with the particular relationship.

Within the reference directory, the addresses of the relationships between *design variables* appear in the left column, whereas the reference numbers are shown in the other five columns depending upon the source of the itemised knowledge. For the relationship between the *design decision variables* "Dd_24 *Glazing material for side windows*" and the *performance variable* "Pe_2 *Heat loss*", for example, since its address is $M_{DdPe}(24, 2)$, the itemised knowledge units extracted from the CIBSE 'Application Manual *Window Design*' whose reference numbers are 81, 89, 91 and 92, as well as that extracted from BS8206 Part 2 whose reference number 77, are obtained (Figure 4.18). Such a reference directory describes the links between the relationships between *design variables* and the itemised knowledge units associated with them, and allows us to obtain the relevant expertise, via the addresses and reference numbers.



Address		Sources of the itemised knowledge units				
MDPe		AM	BS8206-1	BS8206-2	U.B.	Others
1	1	29'	-	**75**	-	-
1	2	29'	-	-	7, **42**	-
...	...	...	...	...	...	...
23	17	-	-	2	-	-
24	2	**81, 89, 91, 92**	-	**77**	-	-
24	3	**81, 89, 92, 93, 94,108**	-	68	-	-
...	...	...	...	...	...	...
...	...	...	...	...	...	...

Figure 4.18 An example of the reference directory

4.3.6 Examination of the relationships between *design variables*

In order to develop a framework describing the sequence of design decisions in the process, the relationships between *design variables* were examined further. To develop a logical sequence of decision-making steps, it was necessary to study the relationships between the *design decision variables* themselves. The relationships between the *performance* and *design decision variables* are vital for the preparation of cross-references, regarding the design criteria and potential conflicts, associated with particular decisions.

The study of the relationships was carried out based upon their matrix-representations. Although the matrices only show whether or not any relationships exist between particular *design variables*, they allow this study to be dealt with by applying mathematical operations, or even by simple examination of rows and columns representing particular *design variables.* In order to develop a framework describing the inter-relationship of design variables for inter-disciplinary building design working, the following studies were carried out.

Firstly, the "M_{DdDd}", i.e. *Design decision-Design decision Matrix*, was studied so that a sequence of design decision-making steps could be developed taking account of the inter-dependency between the design decisions. It was considered that the more elements of "1" found in a particular row, the bigger the influence the design decision represented by the row could have on other design decisions. Such design decisions therefore should be considered prior to those influenced by it. This suggests that a framework of the design decision-making process could be developed depending upon the inter-relationships between the *design decision variables.* Consequently, a logical sequence of design decision making could be defined based upon this structure. In order to develop such a structure, and identify the sequence of design decision-making, the systems engineering methodology of developing a structural model using graph theory was applied to study the matrix M_{DdDd}. This is explained in detail in Appendix D.

Secondly, potential constraints were identified by considering the inter-dependency between a group of the *design decision variables* which needed to be dealt with in parallel. Such a group of *design decision variables* can be identified by developing the structural model of the design decisions, as explained in Appendix D. To identify the potential conflict, the rows of the *Design decision-Design decision Matrix*, M_{DdDd}, representing such groups of the *design decision variables*, were examined. The implication of this examination is that particular care should be taken when a group of *design decision variables* needs to be considered in parallel, so that all the relating performance criteria are fulfilled.

Thirdly, potential conflicts may also exist among a group of *design decision variables* which are related to a particular *performance variable* or *performance variables* (see Figure 4.14 (a)). In other words, if the resulting performance values fail to satisfy the performance criterion or criteria, conflicts will occur between the design decisions, and alteration of the design decision values may well be necessary. Such potential conflicts could be identified by examining a particular *performance variable* column of the *Design decision-Performance Matrix*, M_{DdPe}. If more than one value of "1" existed within a particular *performance variable* column (e.g. column 2 in Figure 4.14 (b)), related to the *design decision variable* rows (rows 1, 2 and 4 in Figure 4.14 (b)), potential conflicts are considered to exist between the corresponding design decisions.

Fourthly, the design criteria associated with each design decision were identified by examining the rows of the *Design decision-Performance Matrix*, M_{DdPe}, which represent a particular design decision (see Figure 4.15). Within the example shown in Figure 4.15, the *performance variables* 2, 3 and 5 should be considered when the *design decision* 4 is to be made, i.e. they are the design criteria for the *design decision* 4 (Figure 4.15 (a)). In this case, the *performance variables* columns 2, 3 and 5 have values of "1" within the row representing the particular *design decision variable* in the matrix (Figure 4.15 (b)). Therefore, the design criteria for a particular *design decision* can be identified by examining the row associated with the design decision.

Finally, the *Information-Performance Matrices*, M_{InPc} and M_{InPe}, as well as *Information-Design decision Matrix*, M_{InDd}, were studied with particular reference to the *information variables*, in order to identify the check points necessary to develop an appropriate brief within the briefing stages. Such check points should help to ensure that every aspect associated with the brief is considered before any design ideas are fully developed.

4.4 A Framework For Inter-disciplinary Building Design Working

The building design process was described in terms of the relationships between the *design variables*. Having examined the relationships, a framework for inter-disciplinary design working was developed in terms of a logical sequence of the design activities and the cross-references between the *design variables*.

4.4.1 A sequence of the design activities

It was decided to establish the sequence of the building design activities in terms of the *design issues* and *design tasks*, in relation to the RIBA *Plan of Work* stages: "*inception*", "*feasibility*", "*outline proposals*", "*scheme design*", and "*detailed design*". The boundaries between these stages do not necessarily represent the demarcation lines between the *design issues*. A *design issue* may not necessarily be completed within a single stage, but may well be resolved during tasks existing across more than one RIBA *Plan of Work* stage.

As discussed in Section 4.2.1, the strategic phase of the building design process was considered to comprise two parts, i.e. "briefing" and "development of a design solution" (see Figure 4.2 in Section 4.2). The sequence of the building design activities was, therefore, established as shown in Table 4.11 (a) and (b), which are in accordance with these two parts, respectively. In these charts, a shaded area indicates the period of time when a particular *design issue* should be considered; and the sign "*" shows the timing for a decision associated with a particular *design variable* (i.e. the timing of establishing the value for a particular *design variable*).

The "*briefing*" phase, which is illustrated in Table 4.11 (a), concerns the *design issues* associated with collecting and studying the relevant information, as well as establishing *performance criteria* (*design issues* (1) to (5)). In other words, the information related to the client's requirements as well as a possible site is collected (*design issues* (1) and (3)), and, by studying it, viable design targets are established (*design issues* (2), (4) and (5)). This can be seen as setting a particular value for each of the *information variables* and establishing the *performance criteria* (*Pc*). Such activities should be carried out within the *inception* stage and the first half of the *feasibility* stage.

Meanwhile, Table 4.11 (b) is associated with the "*development of a design solution*", which is considered to involve seven *design issues*, i.e. "*Design approaches*", "*Building arrangement on the site*", "*Building form*", "*Internal layout*", "*Ventilation methods*", "*Window design*" and "*Artificial lighting design*". It illustrates a sequence of the design decision making in terms of the *design decision variables* associated with these *design issues*, i.e. a logical sequence of the design decision-making steps. The sequence of the design decision-making steps was determined as follows:

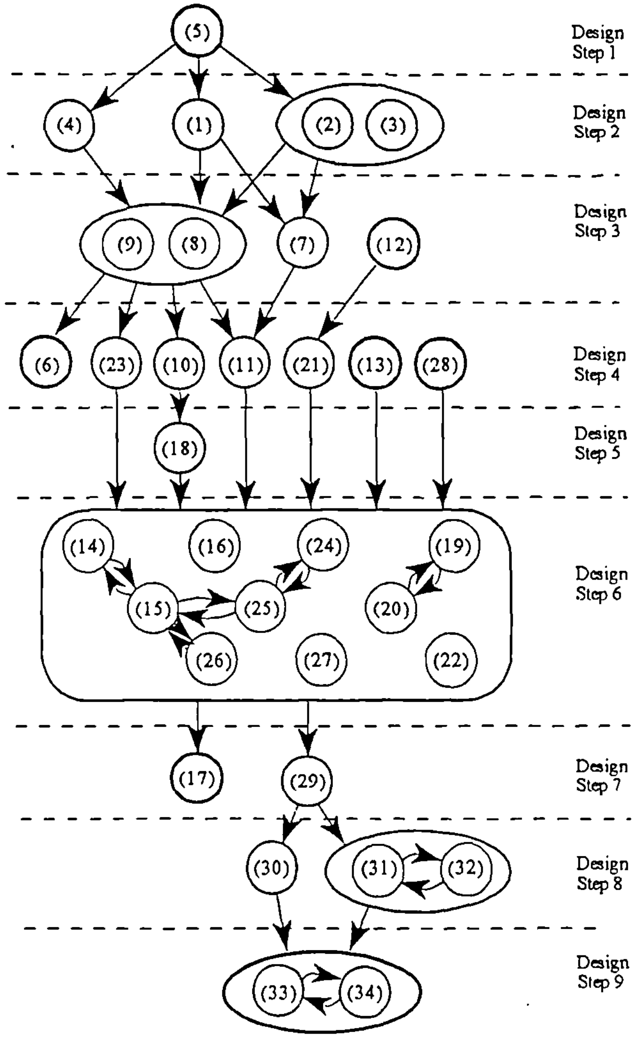
(a) As mentioned in Section 4.3.5, having examined the matrix M_{DdDd}, which describes the relationships between the *design decision variables*, the inter-dependencies between the design decisions were studied. For this examination, the systems engineering methodologies, including graph theory, were utilised. This study is explained in detail in Appendix F. As a consequence, the *design decision variables* were structured in terms of nine *Design Steps*, as shown in Figure 4.19 drawn from Appendix F. The *Design Steps* describe the sequence of the design decision-making based upon the influences between the design decisions, regardless of the *design issues*.

(b) *Design decision variables* classified into *Design Steps* were arranged in relation to the RIBA *Plan of Work* stages, by taking account of the broad timing of the *design issues* shown in Table 4.1 in Section 4.2.2, which was extracted from Table 1 of BS8207.

(c) The design decision sequence associated with a particular *design issue*, such as "*Window design*" and "*Artificial lighting design*", was determined according to the design methodology for the *design issue* described in the published materials, e.g. CIBSE 'Application Manual *Window design*' and CIBSE '*Code for interior lighting*'. These individual design methodologies are explained in Appendix C. Consequently, the sequence of the entire design decision-making steps was developed in relation to the RIBA *Plan of Work* stages, as described in Table 4.11 (b).

During the design process related to the *design issues* within the "*development of a design solution*", a particular stereotype will be chosen at some stage to act as a starting point for the design. Here, the RIBA *Plan of Work* is considered as a management tool. It is understood from Table 4.11 (b) that *design issue* (6) '*Design approaches*' may be undertaken within the second half of the *feasibility* stage after the design targets have been established;

having determined the design approaches, *design issues* (7) to (12) begin to be considered in a parallel manner. Therefore, while more than one *design issue* may need to be considered at the same time within one RIBA *Plan of Work* stage, the design activities associated with a particular *design issue* could spread over more than one RIBA *Plan of Work* stage.



Design Step 1	(5)	Noise insulation priorities
Design Step 2	(1)	Daylight priorities
	(2)	Sunshine priorities
	(3)	View priorities
	(4)	Ventilation priorities
Design Step 3	(7)	Orientation of the building
	(8)	Form of the building
	(9)	Use of rooflights
	(12)	Construction type
Design Step 4	(6)	Position of the building on the site
	(10)	Roof shape
	(11)	Glazing orientation and related glazing area
	(23)	Primary function of side windows
	(21)	Number and position of rooflights
	(13)	Functional connections
	(28)	Reflectance of the interior
Design Step 5	(18)	Rooflight profiles
Design Step 6	(14)	Accommodation plan
	(15)	Room depth
	(16)	Use of natural ventilation
	(19)	Glazing materials for rooflights
	(20)	Glazed area for rooflights
	(22)	Area and dimension of individual rooflight
	(24)	Glazing material for side windows
	(25)	Glazed area for side windows
	(26)	Window shapes and positions
	(27)	Shading devices
Design Step 7	(17)	Need for mechanical ventilation or air-conditioning
	(29)	Function of artificial lighting
Design Step 8	(30)	Lighting system
	(31)	Lamp types
	(32)	Lighting luminaires
Design Step 9	(33)	Arrangement of the luminaires
	(34)	Lighting control system

Figure 4.19 A sequence of the design decision-making regarding daylighting and lighting issues in particular

Table 4.11 (a) A sequence of the design tasks: (1) *Briefing*

Design issue	Design variables	RIBA *Plan of Work* stages	
		Inception	Feasibility (1st half)
(1) General outline of the requirements	In(1_01 Aim of the project	*(3	
	In_02 Budget	*	
	In_03 Timetable	*	
	In_04 Use of the building	*	
	In_05 Accommodation	*	
	In_05 Activities carried out	*	
	In_06 Visual tasks	*	
	In_07 Occupation patterns	*	
(3) Context of the scheme	In_08 Boundaries	*	
	In_09 Daylight availability	*	
	In_10 Sunlight duration	*	
	In_11 View	*	
	In_12 Noise sources	*	
	In_13 Physical pollution	*	
	In_14 Ambient climate	*	
	In_15 Local authorities and statutory regulations	*	
(5) Design criteria, as a result of (2) Design objectives and (4) Feasibility study	Pc(2_01 Energy targets		*
	Pc_03 Thermal comfort level required		*
	Pc_04 Air qualities required		*
	Pc_05 Illuminance level required		*
	Pc_06 Uniformity required		*
	Pc_07 Target ADF		*
	Pc_08 Colour properties required		*
	Pc_13 Noise insulation level required		*
	Pc_16 Cost range criteria		*

N.B. (1: "In" stands for *Information.*
(2: "Pc" stands for *Performance criteria.*
(3: "*" indicates the timing of establishing a value for a particular design value

Table 4.11 (b) A sequence of the design tasks: (2) *Development of a design solution*

N.B. (1: "D.S." stands for *Design Stage*, defined in Appendix D. See Table D.10.
(2: "Dd" stands for *Design decision*.
(3: "*" indicates the timing for a particular design decision to be considered.

Design issue	Design variables	RIBA *Plan of Work* stages								
		Feasibility (2nd half)			Outline proposals			Scheme design	Detail design	
		D.S.1(1	D.S.2	D.S.3	D.S.4	D.S.5	D.S.6	D.S.7	D.S.8	D.S.9
(6) Design approach / priorities	Dd(2_01 Daylight priorities		*(3							
	Dd_02 Sunshine priorities		*							
	Dd_03 View priorities		*							
	Dd_04 Ventilation priorities		*							
	Dd_05 Noise insulation priorities	*								
(7) Building's arrangement on the site	Dd_06 Position of the building on the site				*					
	Dd_07 Orientation of the building			*						
(8) Building form	Dd_08 Form of the building			*						
	Dd_09 Use of rooflights			*						
	Dd_10 Roof shape				*					
	Dd_11 Glazing orientation and related glazing area				*					
	Dd_12 Construction type			*						
(9) Internal layout	Dd_13 Functional connections				*					
	Dd_14 Accommodation plan						*			
	Dd_15 Room depth						*			

Table 4.11 (b) (continued)

Design issue	Design variables	RIBA *Plan of Work* stages								
		Feasibility (2nd half)			Outline proposals			Scheme design	Detail design	
		D.S. 1	D.S.2	D.S.3	D.S.4	D.S.5	D.S.6	D.S.7	D.S.8	D.S.9
(10) Main ventilation methods	Dd_16 Use of natural ventilation						*			
	Dd_17 Need for mechanical ventilation or air-conditioning							*		
(11) Window design / fenestration	Dd_18 Rooflight profiles					*				
	Dd_19 Glazing materials for rooflights						*			
	Dd_20 Glazed area for rooflights						*			
	Dd_21 Number and position of rooflights				*					
	Dd_22 Area and dimension of individual rooflight						*			
	Dd_23 Primary function of side windows				*					
	Dd_24 Glazing materials for side windows						*			
	Dd_25 Glazed area for side windows						*			
	Dd_26 Window shapes and positions						*			
	Dd_27 Shading devices						*			
	Dd_28 Reflectance of the interior				*					
(12) Artificial lighting installation	Dd_29 Function of artificial lighting							*		
	Dd_30 Lighting system								*	
	Dd_31 Lamp types								*	
	Dd_32 Lighting luminaires								*	
	Dd_33 Arrangement of the luminaires									*
	Dd_34 Lighting control system									*

4.4.2 Cross-references

Having examined the matrices representing the relationships between the *design variables*, cross-references were developed in the form of the list of associated *design variables* with regard to each of the individual *design variables*. These lists are presented in Appendix E.3, where a set of the *design variables* associated with a particular *design variable* is shown with its address in terms of the matrix representation. The contents of the lists depend upon the *design variables* with which the sets of variables are associated. Therefore, the lists of *design variables* can be classified into the following four types:

(a) The lists of *design variables* associated with the *information variables* (In)

They contain the *performance criteria* (Pc), *design decision variables* (Dd), and *performance variables for evaluation* (Pe) which may be affected by the conditions represented by the *information variables*. They were obtained by studying the matrices M_{InPc}, M_{InDd} and M_{InPe}, respectively, with particular reference to each of the *information variables*. The relationships between these *design variables* and the *information variables* are involved in the design activities, such as establishing *performance criteria* (design targets), making design decisions, and carrying out evaluation processes. Any of these relationships may not yet need to be considered when the values are established for the *information variables* at the beginning of the design process, i.e. during the inception stage. It was felt, however, that such lists could help the designers have an insight into the forthcoming design activities strongly associated with the outcomes of the inception stage.

(b) The lists of *design variables* with regard to the *performance criteria* (Pc)

They consist of *information variables*. This implies that the conditions (i.e. requirements and constraints) represented by the *information variables* need to be considered when the design targets are established, in relation to *design issue* (5) '*Performance criteria: environmental standards*'. These lists were produced by studying the matrix M_{InPc} with particular reference to each of the *performance criteria* (Pc).

(c) **The lists of *design variables* associated with the *design decision variables* (Dd)**

They may comprise *information variables*, *performance variables for evaluation* (Pe), and *design decision variables*. Here, the *information variables* represent the conditions (e.g. physical and functional constraints) which may affect the design decisions. The *performance variables for evaluation* (Pe) associated with a particular *design decision variable* (see Figure 4.15 (a) in Section 4.3.5) can be involved in both "*evaluation*" and "*synthesis*". They are considered to represent the performance characteristics to be examined in relation to the design decision. In this sense, the list of *performance variables* can be regarded as a set of design criteria which have to be considered when the design decision is made. The *performance variables* also represent the results of the examination, and are considered with their *performance criteria* (Pc) in order to make the associated design decision. Meanwhile, the *design decision variables* which represent the preceding design decisions may restrict subsequent design decisions. Such cross-references were obtained by studying the matrices M_{InDd}, M_{DdPe} and M_{DdDd} with regard to each of the *design decision variables*.

(d) **The lists of *design variables* with regard to the *performance variables for evaluation* (Pe)**

They may involve the *design decision variables* associated with particular *performance variables* (see Figure 4.14 (a) in Section 4.3.5), and the *information variables* which may provide the information required for the evaluation processes. They were obtained by studying the matrices M_{DdPe} and M_{InPe}, respectively, in terms of a particular *performance variable*. Such lists can present the parameters associated with the performance characteristics of the building, and could promote assured evaluation processes.

4.4.3 Design criteria and potential conflicts

Within the framework for inter-disciplinary building design working, the design activities are described in terms of the *design variables* and relationships between them. In order to develop a checklist for inter-disciplinary building design working, it was decided to define the *design criteria* for each of the design decisions and the *potential conflicts* which might occur between the design decisions.

(a) Design criteria

The *design criteria* were considered as the performance variables which have to be considered when a particular design decision is made (see Figure 4.15 (a) in Section 4.3.5). Within the cross-references, the *performance variables* listed in relation to the *design decision variables* are considered as such *design criteria.* These *performance variables* are shown in Table 4.12.

(b) Potential conflicts between the design decisions

Any *potential conflicts* which may arise can be identified based upon the pertinent *design decision variables* cross-referenced with regard to a particular *design decision variable.* Such *design decision variables* are shown in Table 4.13, with regard to each of the *design decision variables.* As discussed in Section 4.2 in relation to the rational description of the building design work, the potential conflicts could be "*local*" if the *design decision variables* of the list belong to the same *design issue* as the *design decision variables* under consideration, whereas they would be "*global*" if the design decision variables originate from other *design issues.* In this case, a greater degree of modification of the design proposals may well be necessary to solve the conflict than in the "local" case. However, the relationships between the *design decision variables* do not necessarily imply potential *conflicts* but, rather, *constraints* imposed by the preceding design decisions. It is, therefore, necessary to examine the itemised knowledge upon which the individual relationships between these *design decision variables* were defined, so as to identify what conflicts might occur for individual cases. The study using graph theory described in Appendix D, nevertheless, identified the *design decision variables* which have mutual relationships between them, i.e. the design decisions which have to be considered at the same time as they may affect each other. It is understood that conflicts are likely to occur between such *design decision variables.* Such *design decision variables* are indicated in bold within Table 4.13.

Further conflicts might occur between design decisions associated via common design criteria (see Figure 4.14 (a) in Section 4.3.5). Such potential conflicts might be found by studying the lists of *design decision variables* which can be associated with a common *performance variable.* But, it was decided not to pursue this aspect, in order to stop the checklist from becoming unnecessarily complicated for the purposes of this study.

Table 4.12 (a) Design criteria based upon the matrix representing the relationships between *design decision variables* (Dd) and *performance variables*(Pe) (1/6)

Design issue	*Design decision variable* and *Design criteria*
Design issue (6) 'Design approach'	**Dd_01 Daylight priorities** Pe_01 Energy consumption $M_{DdPe}(1, 1)$ Pe_02 Heat loss $M_{DdPe}(1, 2)$ Pe_03 Solar gain $M_{DdPe}(1, 3)$ Pe_06 Uniformity of illuminance level $M_{DdPe}(1, 6)$ Pe_07 Average daylight factor (ADF) $M_{DdPe}(1, 7)$ Pe_08 Colour properties $M_{DdPe}(1, 8)$ Pe_09 Appearance / modelling $M_{DdPe}(1, 9)$ Pe_10 Glare and specular reflection $M_{DdPe}(1, 10)$ Pe_11 View $M_{DdPe}(1, 11)$
	Dd_02 Sunshine priorities Pe_01 Energy consumption $M_{DdPe}(2, 1)$ Pe_03 Solar gain $M_{DdPe}(2, 3)$ Pe_10 Glare and specular reflection $M_{DdPe}(2, 10)$
	Dd_03 View priorities Pe_11 View $M_{DdPe}(3, 11)$ Pe_12 Privacy $M_{DdPe}(3, 12)$
	Dd_04 Ventilation priorities No *performance variable for evaluation* (Pe) was associated with this *design decision variable*.
	Dd_05 Noise insulation priorities No *performance variable for evaluation* (Pe) was associated with this *design decision variable*.
Design issue (7) 'Building arrangement on the site'	**Dd_06 Position of the building on the site** Pe_03 Solar gain $M_{DdPe}(6, 3)$ Pe_07 Average daylight factor (ADF) $M_{DdPe}(6, 7)$ Pe_11 View $M_{DdPe}(6, 11)$ Pe_12 Privacy $M_{DdPe}(6, 12)$ Pe_15 Overshadowing $M_{DdPe}(6, 15)$
	Dd_07 Orientation of the building Pe_03 Solar gain $M_{DdPe}(7, 3)$ Pe_07 Average daylight factor (ADF) $M_{DdPe}(7, 7)$ Pe_11 View $M_{DdPe}(7, 11)$ Pe_12 Privacy $M_{DdPe}(7, 12)$ Pe_15 Overshadowing $M_{DdPe}(7, 15)$

Table 4.12 (b) Design criteria (2/6)

Design issue	*Design decision variable* and *Design criteria*		
Design issue (8) 'Building form'	**Dd_08**	**Form of the building**	
	Pe_01	Energy consumption	$M_{DdPe}(8, 1)$
	Pe_02	Heat loss	$M_{DdPe}(8, 2)$
	Pe_03	Solar gain	$M_{DdPe}(8, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(8, 7)$
	Pe_12	Privacy	$M_{DdPe}(8, 12)$
	Pe_15	Overshadowing	$M_{DdPe}(8, 15)$
	Pe_16	Cost	$M_{DdPe}(8, 16)$
	Pe_17	Aesthetics	$M_{DdPe}(8, 17)$
	Dd_09	**Use of rooflights**	
	Pe_02	Heat loss	$M_{DdPe}(9, 2)$
	Pe_03	Solar gain	$M_{DdPe}(9, 3)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(9, 6)$
	Pe_09	Appearance / modelling	$M_{DdPe}(9, 9)$
	Dd_10	**Roof shape**	
	Pe_03	Solar gain	$M_{DdPe}(10, 3)$
	Dd_11	**Glazing orientation and related glazing area**	
	Pe_01	Energy consumption	$M_{DdPe}(11, 1)$
	Pe_02	Heat loss	$M_{DdPe}(11, 2)$
	Pe_03	Solar gain	$M_{DdPe}(11, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(11, 7)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(11, 10)$
	Pe_12	Privacy	$M_{DdPe}(11, 12)$
	Dd_12	**Construction type**	
	Pe_01	Energy consumption	$M_{DdPe}(12, 1)$
	Pe_02	Heat loss	$M_{DdPe}(12, 2)$
Design issue (9) 'Internal layout'	**Dd_13**	**Functional connections of internal spaces**	
	Pe_05	Illuminance level on a working plane	$M_{DdPe}(13, 5)$
	Dd_14	**Accommodation plan**	
	Pe_03	Solar gain	$M_{DdPe}(14, 3)$
	Pe_05	Illuminance level on a working planc	$M_{DdPe}(14, 5)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(14, 7)$
	Pe_08	Colour properties	$M_{DdPe}(14, 8)$
	Pe_09	Appearance / modelling	$M_{DdPe}(14, 9)$
	Dd_15	**Room depth**	
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(15, 7)$
	Pe_11	View	$M_{DdPe}(15, 11)$

Table 4.12 (c) Design criteria (3/6)

Design issue	*Design decision variable* and *Design criteria*		
Design issue (10) 'Main ventilation methods'	**Dd_16**	**Use of natural ventilation**	
	Pe_01	Energy consumption	$M_{DdPe}(16, 1)$
	Pe_02	Heat loss	$M_{DdPe}(16, 2)$
	Dd_17	**Need for mechanical ventilation or air-conditioning**	
	Pe_01	Energy consumption	$M_{DdPe}(17, 1)$
	Pe_02	Heat loss	$M_{DdPe}(17, 2)$
Design issue (11) 'Window design / fenestration'	**Dd_18**	**Rooflight profile**	
	Pe_02	Heat loss	$M_{DdPe}(18, 2)$
	Pe_03	Solar gain	$M_{DdPe}(18, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(18, 7)$
	Pe_09	Appearance / modelling	$M_{DdPe}(18, 9)$
	Dd_19	**Glazing materials for rooflight**	
	Pe_02	Heat loss	$M_{DdPe}(19, 2)$
	Pe_03	Solar gain	$M_{DdPe}(19, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(19, 7)$
	Pe_08	Colour properties	$M_{DdPe}(19, 8)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(19, 10)$
	Dd_20	**Glazed area for rooflights**	
	Pe_01	Energy consumption	$M_{DdPe}(20, 1)$
	Pe_02	Heat loss	$M_{DdPe}(20, 2)$
	Pe_03	Solar gain	$M_{DdPe}(20, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(20, 7)$
	Dd_21	**Number and position of rooflights**	
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(21, 6)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(21, 10)$
	Pe_14	Structure	$M_{DdPe}(21, 14)$
	Dd_22	**Area and dimension of individual rooflights**	
	Pe_02	Heat loss	$M_{DdPe}(22, 2)$
	Pe_03	Solar gain	$M_{DdPe}(22, 3)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(22, 6)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(22, 7)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(22, 10)$

Table 4.12 (d) Design criteria (4/6)

Design issue	*Design decision variable* and *Design criteria*		
Design issue (11) 'Window design / fenestration'	**Dd_23**	**Primary function of side windows**	
	Pe_09	Appearance / modelling	$M_{DdPe}(23, 9)$
	Pe_17	Aesthetics	$M_{DdPe}(23, 17)$
	Dd_24	**Glazing materials for side windows**	
	Pe_02	Heat loss	$M_{DdPe}(24, 2)$
	Pe_03	Solar gain	$M_{DdPe}(24, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(24, 7)$
	Pe_08	Colour properties	$M_{DdPe}(24, 8)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(24, 10)$
	Pe_13	Noise level within the building	$M_{DdPe}(24, 13)$
	Pe_17	Aesthetics	$M_{DdPe}(24, 17)$
	Dd_25	**Glazed area for side windows**	
	Pe_01	Energy consumption	$M_{DdPe}(25, 1)$
	Pe_02	Heat loss	$M_{DdPe}(25, 2)$
	Pe_03	Solar gain	$M_{DdPe}(25, 3)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(25, 7)$
	Pe_11	View	$M_{DdPe}(25, 11)$
	Pe_13	Noise level within the building	$M_{DdPe}(25, 13)$
	Pe_17	Aesthetics	$M_{DdPe}(25, 17)$
	Dd_26	**Window shapes and positions**	
	Pe_02	Heat loss	$M_{DdPe}(26, 2)$
	Pe_03	Solar gain	$M_{DdPe}(26, 3)$
	Pe_04	Ventilation performance (air change)	$M_{DdPe}(26, 4)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(26, 6)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(26, 7)$
	Pe_09	Appearance / modelling	$M_{DdPe}(26, 9)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(26, 10)$
	Pe_11	View	$M_{DdPe}(26, 11)$
	Pe_12	Privacy	$M_{DdPe}(26, 12)$
	Pe_14	Structure	$M_{DdPe}(26, 14)$
	Pe_17	Aesthetics	$M_{DdPe}(26, 17)$

Table 4.12 (e) Design criteria (5/6)

Design issue	*Design decision variable* and *Design criteria*		
Design issue (11) 'Window design / fenestration' (continued)	**Dd_27**	**Shading devices**	
	Pe_01	Energy consumption	$M_{DdPe}(27, 1)$
	Pe_02	Heat loss	$M_{DdPe}(27, 2)$
	Pe_03	Solar gain	$M_{DdPe}(27, 3)$
	Pe_04	Ventilation performance (air change)	$M_{DdPe}(27, 4)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(27, 6)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(27, 7)$
	Pe_08	Colour properties	$M_{DdPe}(27, 8)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(27, 10)$
	Pe_11	View	$M_{DdPe}(27, 11)$
	Pe_17	Aesthetics	$M_{DdPe}(27, 17)$
	Dd_28	**Reflectance of the interior**	
	Pe_05	Illuminance level on a working plane	$M_{DdPe}(28, 5)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(28, 6)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(28, 7)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(28, 10)$
	Pe_17	Aesthetics	$M_{DdPe}(28, 17)$
Design issue (12) 'Artificial lighting installation'	**Dd_29**	**Function of artificial lighting**	
	Pe_01	Energy consumption	$M_{DdPe}(29, 1)$
	Pe_05	Illuminance level on a working plane	$M_{DdPe}(29, 5)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(29, 6)$
	Pe_07	Average daylight factor (ADF)	$M_{DdPe}(29, 7)$
	Pe_08	Colour properties	$M_{DdPe}(29, 8)$
	Pe_09	Appearance / modelling	$M_{DdPe}(29, 9)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(29, 10)$
	Dd_30	**Lighting system**	
	Pe_01	Energy consumption	$M_{DdPe}(30, 1)$
	Pe_05	Illuminance level on a working plane	$M_{DdPe}(30, 5)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(30, 6)$
	Pe_16	Cost	$M_{DdPe}(30, 16)$
	Dd_31	**Lamp types**	
	Pe_01	Energy consumption	$M_{DdPe}(31, 1)$
	Pe_08	Colour properties	$M_{DdPe}(31, 8)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(31, 10)$
	Pe_16	Cost	$M_{DdPe}(31, 16)$
	Dd_32	**Lighting luminaires**	
	Pe_01	Energy consumption	$M_{DdPe}(32, 1)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(32, 10)$
	Pe_16	Cost	$M_{DdPe}(32, 16)$

Table 4.12 (f) Design criteria (6/6)

Design issue	*Design decision variable* and *Design criteria*		
Design issue (12) 'Artificial lighting installation' (continued)	**Dd_33**	**Arrangement of the luminaires**	
	Pe_01	Energy consumption	$M_{DdPe}(33, 1)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(33, 6)$
	Pe_09	Appearance / modelling	$M_{DdPe}(33, 9)$
	Pe_10	Glare and specular reflection	$M_{DdPe}(33,10)$
	Pe_16	Cost	$M_{DdPe}(33, 16)$
	Dd_34	**Lighting control system**	
	Pe_01	Energy consumption	$M_{DdPe}(34, 1)$
	Pe_06	Uniformity of illuminance level	$M_{DdPe}(34, 6)$
	Pe_16	Cost	$M_{DdPe}(34, 16)$

Table 4.13 (a) Potential conflicts based upon the matrix representing the relationships between *design decision variables* (Dd) themselves (1/7)

Key: (L) Local conflict; (G) Global conflict

(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (6) *Design approach / priorities*	Dd_01	Daylight priorities	Dd_05 (L)	Noise insulation priorities	$M_{DdDd}(5, 1)$
	Dd_02	Sunshine priorities	**Dd_03** (L)	**View priorities**	$M_{DdDd}(3, 2)$
			Dd_05 (L)	Noise insulation priorities	$M_{DdDd}(5, 2)$
	Dd_03	View priorities	**Dd_02** (L)	**Sunshine priorities**	$M_{DdDd}(3, 2)$
	Dd_04	Ventilation priorities	Dd_05 (L)	Noise insulation priorities	$M_{DdDd}(5, 4)$
	Dd_05	Noise insulation priorities	No *design decision variable* (Dd) was associated with this *design decision variable* in terms of potential conflicts.		
Design issue (7) *Building's arrangement on the site*	Dd_06	Position of the building on the site	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 6)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 6)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 6)$
	Dd_07	Orientation of the building	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 7)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 7)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 7)$
Design issue (8) *Building form*	Dd_08	Form of the building	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 8)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 8)$
			Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 8)$
			Dd_09 (L)	**Use of rooflights**	$M_{DdDd}(9, 8)$

Table 4.13 (b) Potential conflicts (2/7) Key: (L) Local conflict; (G) Global conflict
(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (8) *Building form* (continued)	Dd_09	Use of rooflights	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 9)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 9)$
			Dd_08 (L)	**Form of the building**	$M_{DdDd}(8, 9)$
	Dd_10	Roof shape	Dd_08 (L)	Form of the building	$M_{DdDd}(8, 10)$
			Dd_09 (L)	Use of rooflights	$M_{DdDd}(9, 10)$
	Dd_11	Glazing orientation and related glazing area	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 11)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 11)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 11)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 11)$
			Dd_07 (G)	Orientation of the building	$M_{DdDd}(7, 11)$
			Dd_08 (L)	Form of the building	$M_{DdDd}(8, 11)$
	Dd_12	Construction type	No *design decision variable* (Dd) was associated with this *design decision variable* in terms of potential conflicts.		
Design issue (9) *Internal layout*	Dd_13	Functional connections of internal spaces	No *design decision variable* (Dd) was associated with this *design decision variable* in terms of potential conflicts.		
	Dd_14	Accommodation plan	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 14)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 14)$
			Dd_13 (L)	Functional connections	$M_{DdDd}(13, 14)$
			Dd_15 (L)	**Room depth**	$M_{DdDd}(15, 14)$

Table 4.13 (c) Potential conflicts (3/7) Key: (L) Local conflict; (G) Global conflict
(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (9) *Internal layout* (continued)	Dd_15	Room depth	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 15)$
			Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 15)$
			Dd_14 (L)	**Accommodation plan**	$M_{DdDd}(14, 25)$
			Dd_20 (G)	**Glazed area for rooflights**	$M_{DdDd}(20, 15)$
			Dd_21 (G)	Number and position of rooflights	$M_{DdDd}(21, 15)$
			Dd_22 (G)	**Area and dimension of individual rooflight**	$M_{DdDd}(22, 15)$
			Dd_25 (G)	**Glazed area for side windows**	$M_{DdDd}(25, 15)$
			Dd_26 (G)	**Window shapes and positions**	$M_{DdDd}(26, 15)$
			Dd_28 (G)	Reflectance of the interior	$M_{DdDd}(28, 15)$
Design issue (10) *Main ventilation methods*	Dd_16	Use of natural ventilation	Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 16)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 16)$
			Dd_15 (G)	**Room depth**	$M_{DdDd}(15, 16)$
	Dd_17	Need for mechanical ventilation or air-conditioning	Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 17)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 17)$
			Dd_16 (L)	Use of natural ventilation	$M_{DdDd}(16, 17)$
Design issue (11) *Window design / fenestration*	Dd_18	Rooflight profile	Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 18)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 18)$
			Dd_09 (G)	Use of rooflights	$M_{DdDd}(9, 18)$
			Dd_10 (G)	Roof shape	$M_{DdDd}(10,18)$
	Dd_19	Glazing materials for rooflight	Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 19)$
			Dd_20 (L)	**Glazed area for rooflights**	$M_{DdDd}(20, 19)$

Table 4.13 (d) Potential conflicts (4/7) Key: (L) Local conflict; (G) Global conflict
(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (11) *Window design / fenestration* (continued)	Dd_20	Glazed area for rooflights	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 20)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 20)$
			Dd_19 (L)	**Glazing materials for rooflights**	$M_{DdDd}(19, 20)$
			Dd_27 (L)	**Shading devices**	$M_{DdDd}(27, 20)$
			Dd_28 (L)	Reflectance of the interior	$M_{DdDd}(28, 20)$
	Dd_21	Number and position of rooflights	Dd_12 (G)	Construction type	$M_{DdDd}(12, 21)$
	Dd_22	Area and dimension of individual rooflights	Dd_11 (G)	Glazing orientation and related glazing area	$M_{DdDd}(11, 22)$
			Dd_18 (L)	Rooflight profiles	$M_{DdDd}(18, 22)$
			Dd_20 (L)	**Glazed area for rooflights**	$M_{DdDd}(20, 22)$
			Dd_21 (L)	Number and position of rooflights	$M_{DdDd}(21, 22)$
	Dd_23	Primary function of side windows	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 23)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 23)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 23)$
	Dd_24	Glazing materials for side windows	Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 24)$
			Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 24)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 24)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 24)$
			Dd_11 (G)	Glazing orientation and related glazing area	$M_{DdDd}(11, 24)$
			Dd_16 (G)	**Use of natural ventilation**	$M_{DdDd}(16, 24)$
			Dd_23 (L)	Primary function of side windows	$M_{DdDd}(23, 24)$
			Dd_25 (L)	**Glazed area for side windows**	$M_{DdDd}(25, 24)$

Table 4.13 (e) Potential conflicts (5/7) Key: (L) Local conflict; (G) Global conflict
(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (11) *Window design / fenestration* (continued)	Dd_25	Glazed area for side windows	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 25)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 25)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 25)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 25)$
			Dd_11 (G)	Glazing orientation and related glazing area	$M_{DdDd}(11, 25)$
			Dd_12 (G)	Construction type	$M_{DdDd}(12, 25)$
			Dd_14 (G)	**Accommodation plan**	$M_{DdDd}(14, 25)$
			Dd_15 (G)	**Room depth**	$M_{DdDd}(15, 25)$
			Dd_23 (L)	Primary function of side windows	$M_{DdDd}(23, 25)$
			Dd_24 (L)	**Glazing material for side windows**	$M_{DdDd}(24, 25)$
			Dd_27 (L)	**Shading devices**	$M_{DdDd}(27, 25)$
			Dd_28 (L)	Reflectance of the interior	$M_{DdDd}(28, 25)$
	Dd_26	Window shapes and positions	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 26)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 26)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 26)$
			Dd_04 (G)	Ventilation priorities	$M_{DdDd}(4, 26)$
			Dd_05 (G)	Noise insulation priorities	$M_{DdDd}(5, 26)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 26)$
			Dd_12 (G)	Construction type	$M_{DdDd}(12, 26)$
			Dd_15 (G)	**Room depth**	$M_{DdDd}(15, 26)$
			Dd_16 (G)	**Use of natural ventilation**	$M_{DdDd}(16, 26)$
			Dd_23 (L)	Primary function of side windows	$M_{DdDd}(23, 26)$
			Dd_24 (L)	**Glazing material for side windows**	$M_{DdDd}(24, 26)$

Table 4.13 (f) Potential conflicts (6/7) Key: (L) Local conflict; (G) Global conflict

(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (11) *Window design / fenestration* (continued)	Dd_27	Shading devices	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1, 27)$
			Dd_02 (G)	Sunshine priorities	$M_{DdDd}(2, 27)$
			Dd_03 (G)	View priorities	$M_{DdDd}(3, 27)$
			Dd_09 (G)	Use of rooflights	$M_{DdDd}(9, 27)$
			Dd_11 (G)	Glazing orientation and related glazing area	$M_{DdDd}(11,27)$
			Dd_16 (G)	**Use of natural ventilation**	$M_{DdDd}(16, 27)$
			Dd_18 (L)	Rooflight profiles	$M_{DdDd}(18, 27)$
			Dd_21 (L)	Number and position of rooflights	$M_{DdDd}(21, 27)$
			Dd_22 (L)	**Area and dimension of individual rooflight**	$M_{DdDd}(22, 27)$
			Dd_24 (L)	**Glazing material for side windows**	$M_{DdDd}(24, 27)$
			Dd_26 (L)	**Window shapes and positions**	$M_{DdDd}(26, 27)$
	Dd_28	Reflectance of the interior	No *design decision variable* (Dd) was associated with this *design decision variable* in terms of potential conflicts.		
Design issue (12) *Artificial lighting installation*	Dd_29	Function of artificial lighting	Dd_01 (G)	Daylight priorities	$M_{DdDd}(1,29)$
			Dd_08 (G)	Form of the building	$M_{DdDd}(8, 29)$
			Dd_11 (G)	Glazing orientation and related glazing area	$M_{DdDd}(11, 29)$
			Dd_15 (G)	Room depth	$M_{DdDd}(15, 29)$
			Dd_26 (G)	Window shapes and positions	$M_{DdDd}(26, 29)$
			Dd_28 (G)	Reflectance of the interior	$M_{DdDd}(28, 29)$

Table 4.13 (g) Potential conflicts (7/7) Key: (L) Local conflict; (G) Global conflict
(*Design decision variables* in bold indicate those which should be considered interactively.)

Design issue	*Design decision variable*		*Associated design decisions with which conflicts may occur*		
Design issue (12) *Artificial lighting installation* (continued)	Dd_30	Lighting system	Dd_21 (G)	Number and position of rooflights	$M_{DdDd}(21, 30)$
			Dd_26 (G)	Window shapes and positions	$M_{DdDd}(26, 30)$
			Dd_29 (L)	Function of artificial lighting	$M_{DdDd}(29, 30)$
	Dd_31	Lamp types	Dd_26 (G)	Window shapes and positions	$M_{DdDd}(26, 31)$
			Dd_29 (L)	Function of artificial lighting	$M_{DdDd}(29, 31)$
			Dd_32 (L)	**Lighting luminaires**	$M_{DdDd}(32, 31)$
	Dd_32	Lighting luminaires	**Dd_31** (L)	**Lamp types**	$M_{DdDd}(31, 32)$
	Dd_33	Arrangement of the luminaires	Dd_21 (G)	Number and position of rooflights	$M_{DdDd}(21, 33)$
			Dd_26 (G)	Window shapes and positions	$M_{DdDd}(26, 33)$
			Dd_29 (L)	Function of artificial lighting	$M_{DdDd}(29, 33)$
			Dd_34 (L)	**Lighting control system**	$M_{DdDd}(34, 33)$
	Dd_34	Lighting control system	Dd_29 (L)	Function of artificial lighting	$M_{DdDd}(29, 34)$
			Dd_30 (L)	Lighting system	$M_{DdDd}(30, 34)$
			Dd_31 (L)	Lamp types	$M_{DdDd}(31, 34)$
			Dd_33 (L)	**Arrangement of the luminaires**	$M_{DdDd}(33, 34)$

4.5 A Checklist for Inter-disciplinary Building Design Working

Based upon the framework developed in Section 4.4, a checklist for inter-disciplinary design working was eventually produced using the information extracted from publications. In the checklist, the building design process in relation to daylighting and lighting design was divided into 12 *design issues*, in accordance with its rational description defined in Section 4.4. *Design tasks* associated with a particular *design issue* are presented in a logical sequence, so that they can be dealt with in a step-by-step manner.

Figure 4.18 presents a block diagram of the checklist, where the *design issues* are shown in parallel with the RIBA *Plan of Work* stages, as well as a series of steps. The steps within the *Briefing* phase accord with the RIBA *Plan of Work* stages, whereas those within the *development of a design solution* are represented by *Design Steps*, which were established when the inter-dependencies between the design decisions were studied in Appendix F. The *design tasks* associated with a particular *design issue* are indicated in relation to these *Design Steps*. This diagram suggests that more than one *design issue* may be carried out simultaneously involving interaction between them. It also indicates that more than one *design task* originating from a particular *design issue* should be undertaken within one *Design Step*.

The checklist contains "watch points" for individual *design tasks* which depict the parallel inter-disciplinary aspects of the building design process. They were produced by studying the itemised knowledge based upon the cross-references. Since these "watch points" are related to the vital design criteria and potential conflicts associated with a particular *design task*, the checklist can have process checking capability. Full description of the checklist is contained in Appendix G of this thesis.

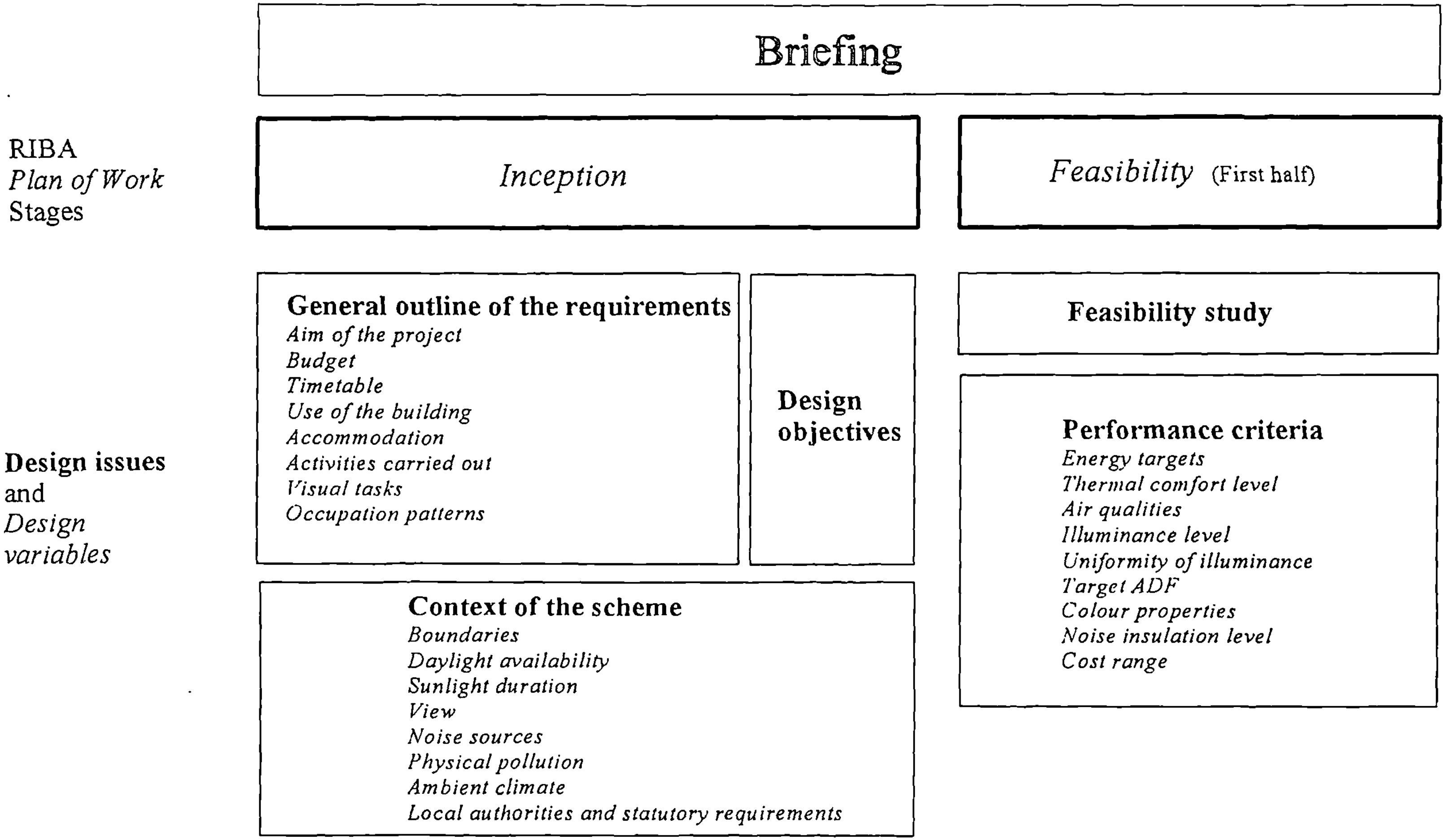


Figure 4.20(a) A block diagram of the checklist (1): "Briefing" (*Inception* and *Feasibility*)

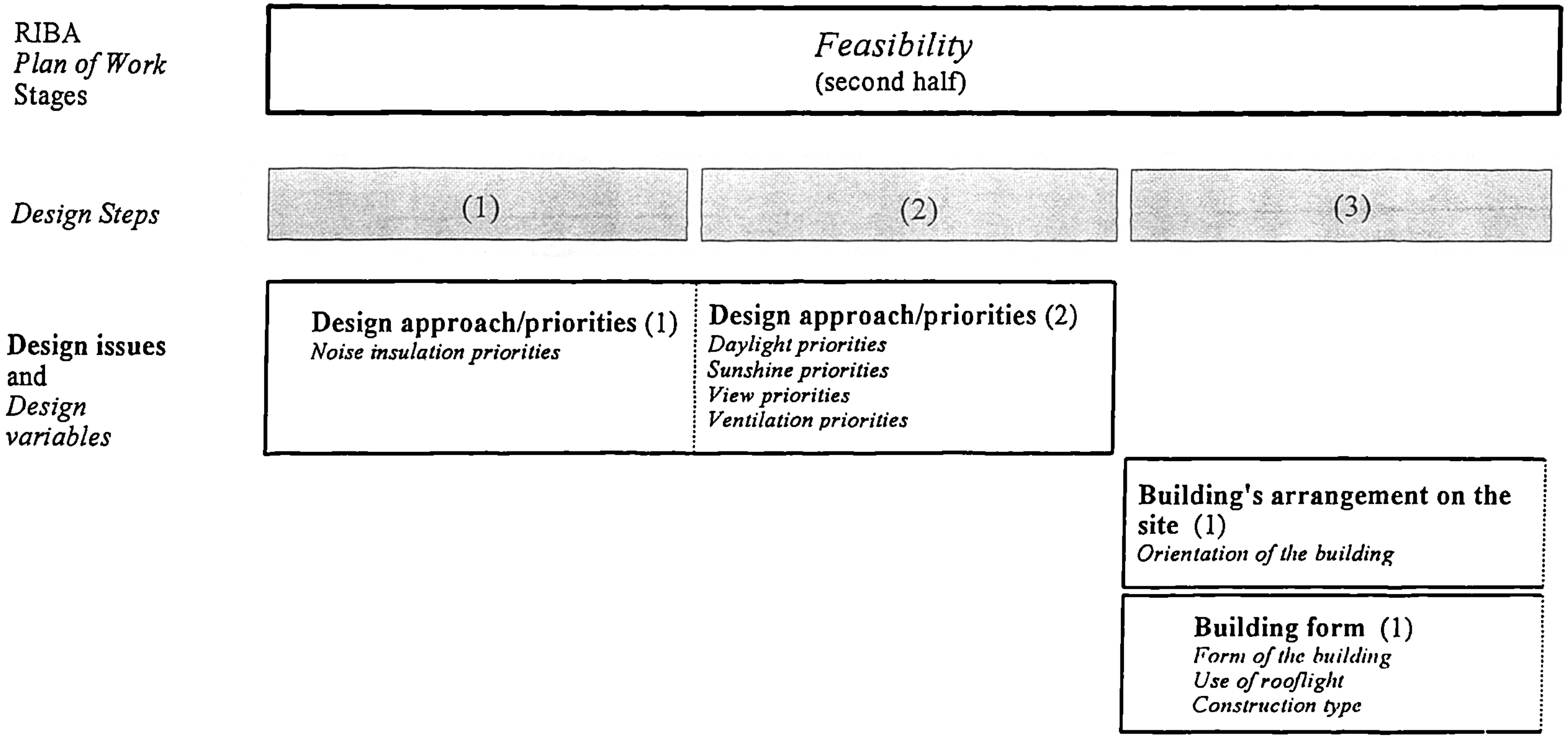
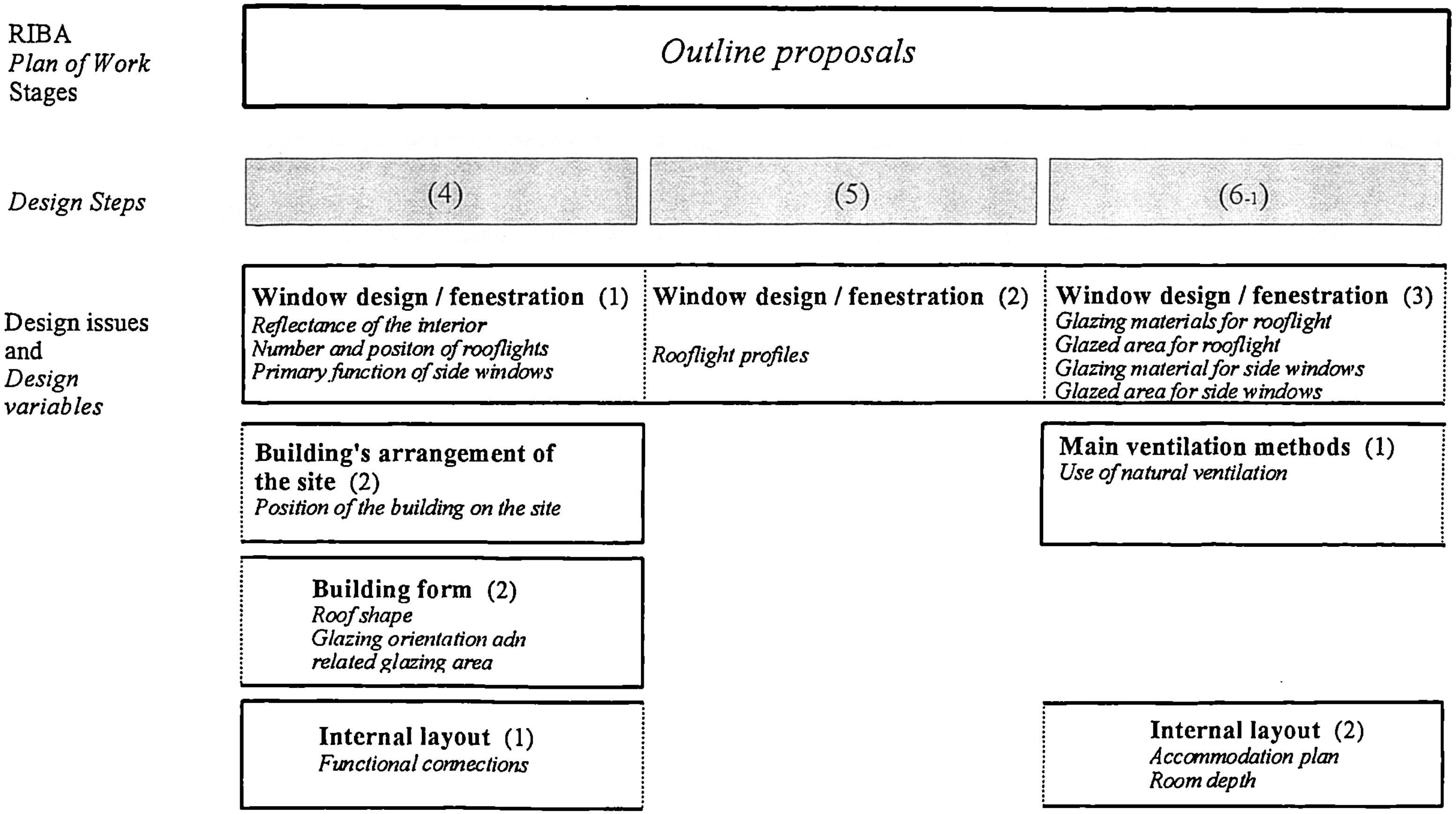


Figure 4.20(b) A block diagram of the checklist (2):
"Development of a design solution": *Feasibility* (*Design Stage* (1)-(3))



RIBA *Plan of Work* Stages	*Outline proposals*		
Design Steps	(4)	(5)	(6-1)
Design issues and *Design variables*	**Window design / fenestration** (1) *Reflectance of the interior* *Number and positon of rooflights* *Primary function of side windows*	**Window design / fenestration** (2) *Rooflight profiles*	**Window design / fenestration** (3) *Glazing materials for rooflight* *Glazed area for rooflight* *Glazing material for side windows* *Glazed area for side windows*
	Building's arrangement of the site (2) *Position of the building on the site*		**Main ventilation methods** (1) *Use of natural ventilation*
	Building form (2) *Roof shape* *Glazing orientation adn related glazing area*		
	Internal layout (1) *Functional connections*		**Internal layout** (2) *Accommodation plan* *Room depth*

Figure 4.20(c) A block diagram of the checklist (3): "Development of a design solution": *Outline proposals* (*Design Step* (4)-(6-1))

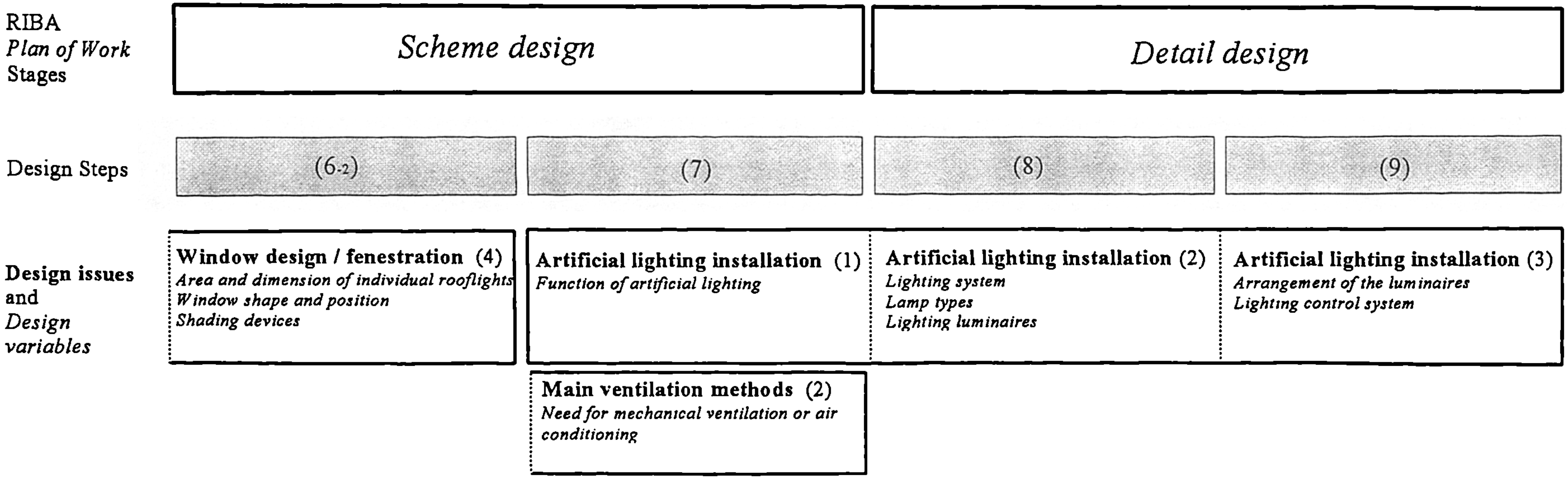


Figure 4.20(d) A block diagram of the checklist (4):
"Development of a design solution": *Scheme design* and *Detail design* (*Design Step* (6-2)-(9))

Chapter 5

Chapter 5

COMPUTER-BASED DESIGN AID AND APPLICATION OF AN INTELLIGENT KNOWLEDGE-BASED SYSTEM FOR INTER-DISCIPLINARY DESIGN WORKING

In this chapter, a computer-based design aid for inter-disciplinary building design working, and the application of intelligent knowledge-based systems (IKBS) techniques, are discussed. Firstly, in Section 5.1, the need for a computer-based design aid is argued in terms of promoting inter-disciplinary building design working as well as the effective use of design knowledge. Then, in order to provide this aid, the application of IKBS techniques is proposed. Subsequently, in Section 5.2, the fundamental concepts of an IKBS are introduced, and its potential application is reviewed in a general sense. Then, the application of an IKBS is discussed in Section 5.3, in terms of the advantages of this approach and the application domain of an IKBS for inter-disciplinary building design working, and the required functions of the IKBS are considered.

5.1 Introduction

It was argued in Section 1.3 of Chapter 1 that, in order to improve the productivity of a building design process as well as maintaining quality-assurance of a design of a building, it would be vital to:

(a) promote inter-disciplinary design working (Section 1.3.1),

(b) aid effective use of design expertise belonging to a handful of knowledgable designers as well as design information which often takes written form (Section 1.3.3), and

(c) make full use of the power of discipline-specific but sophisticated design software packages (Section 1.3.2).

Application (c) could lead to the development of an intelligent front end (IFE), but (a) and (b) are going to be the main interest of this project. Consequently, a framework for inter-disciplinary building design working was developed with particular reference to daylighting and lighting design aspects as described in Chapter 4.

This project intends to develop a computer-based design aid which aims to attain the following objectives:

(1) Promoting inter-disciplinary building design working:

The framework developed in Chapter 4 embodies a logical sequence of design activities and the relationships between design variables in terms of a checklist and cross-references. The framework also allows the itemised knowledge upon which the framework was developed, to be retrieved via its reference directory. It may not be easy to put this framework itself into practice, without the use of a computer, because of the sheer complexity arising from its multilateral checking. Introducing a computer-based design aid is, therefore, deemed to be necessary in order to implement the framework and, ultimately, to promote inter-disciplinary building design working in practice.

(2) Democratising expert knowledge:

Expertise acquired through practice tends to belong to a limited number of experienced individuals, and is often lost when they leave practice for alternative employment. It is desirable to maintain such expert knowledge and make it available for less-experienced designers. In this sense, the framework developed in Chapter 4 involves some amount of knowledge regarding inter-disciplinary building design working, in terms of itemised knowledge units, although they were extracted from published materials, rather than directly from human designers. In order to enhance the effective use of the knowledge, a computer-based design aid which allows relevant knowledge units to be accessed easily and quickly during the design process would be advantageous.

(3) Making design information more extensive and accessible:

Designers often seek design information, or data, either by questioning their knowledgeable colleagues or referring to written materials. There is, however, an unwillingness among designers to consult written sources, because it is regarded as a time consuming activity [Mackinder and Marvin, 1982; see Appendix A]. It is, therefore, desirable to provide appropriate information in a form which is easily assimilated, whenever it is required during the design process.

For this project, the application of intelligent knowledge-base systems (IKBS) techniques was considered in order to develop a computer-based design aid which is capable of achieving these objectives. In the next section, the fundamental ideas of an IKBS, and its potential application, are explained. The techniques used to develop such an IKBS will be explained Chapter 6 in relation to the development of a prototype system for inter-disciplinary building design working.

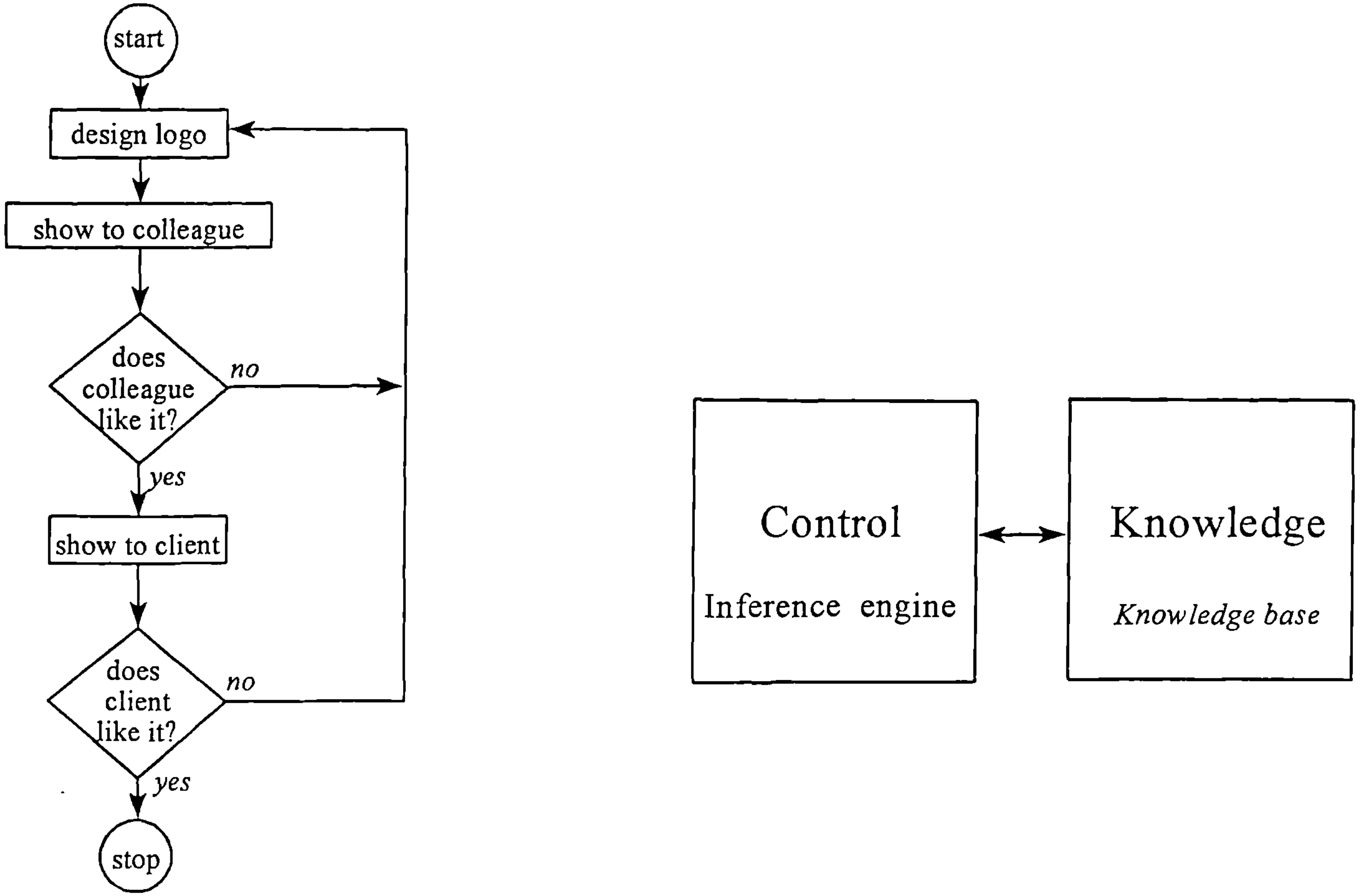
5.2 Intelligent Knowledge-Based Systems

5.2.1 An intelligent knowledge-based system

An intelligent knowledge-based system (IKBS) is a computer system that embodies an explicit representation of knowledge concerning a specific application domain. Here 'knowledge' implies a set of principles for organising the attributes of individual events and entities, explaining individual facts and providing an understanding of the domain. It can be used to solve problems which may require the application of expert knowledge, e.g. technical and professional tasks in a certain domain, such as medicine, engineering, chemistry, law and architecture. Development of an IKBS involves *knowledge acquisition* (collecting and organising the knowledge regarding a particular application domain) and *knowledge representation* (expressing, or coding, the knowledge in a particular manner such as "*IF-THEN*" rules).

The difference between an IKBS and a conventional computer program is the separation of knowledge from a control (reasoning) mechanism of the system (Figure 5.1). In a conventional computer program, knowledge is bound up in control statements such as procedural calls, conditions and loops (Figure 5.1 (a)). Consequently, the operations of the program are predetermined, and the knowledge can hardly be seen explicitly from the procedure of the program. In an IKBS, on the other hand, the knowledge about a particular domain is stored in a knowledge base, and separated from the reasoning mechanism of the system, called the *inference engine*, which comprises theorem provers or search algorithms (Figure 5.1 (b)). As a result, while the inference engine (reasoning mechanism) is general purpose, the knowledge base is domain-specific as it contains an explicit representation of underlying rules of a particular subject area. Such an IKBS architecture could, therefore, allow new applications to be developed by constructing a knowledge-base containing the expert knowledge with regard to a specific subject, with hardly any concern for its control mechanism. In the future it could be extended and improved by adding and/or modifying its knowledge.

Figure 5.1



(a) Conventional computer program: an example of procedural knowledge as a flow chart [Coyne et al., 1990, pp.35].

(b) IKBS: the key to knowledge-based systems lies in separating knowledge from control [Coyne et al., 1990, pp.37].

Figure 5.1 The difference between an IKBS and a conventional computer program.

5.2.2 Types of the application of intelligent knowledge-based systems

Intelligent knowledge-based systems (IKBS) have been applied to various subjects, from diagnosis to pattern recognition. One of the most prominent IKBS applications has been the expert system. An expert system is a computer program which can simulate the behaviour of a human expert within a specific area of expertise [*Leonardo User's Guide*, 1989]. Its knowledge-base should contain the expertise of a specific area, and the system should be capable of solving problems of this field as competently as a human expert. It should also be able to explain its reasoning process in an understandable way in terms of *why* and *how* the system has derived its result.

The application of IKBS is not necessarily limited to simulating the behaviour of a human expert, however. Considering their objectives, the possible IKBS applications could be categorized into five major types as follows:

(a) problem-solving systems
(b) decision support systems
(c) consultation systems
(d) intelligent computer-aided instruction systems, and
(e) intelligent front ends.

(a) **Problem-solving systems** reason and offer optional advice to solve a problem. Artificial intelligence (AI) research in '60s and early '70s focused on well-defined laboratory problems, such as chess and puzzles. These problems can be characterised as having an "initial state" of an object, a "final state (goal)", and relatively limited numbers of "operations", "state changes" and "constraints". A problem-solving system for such a specific domain uses a list of operations which are completely defined in terms of their effect on the current state of the object. The system attempts to establish a sequence of the basic operations that accomplishes the goal effectively, or to prove that a set of applications of the operations results in the final state. In this sense, such a problem-solving system can be inference-oriented, rather than knowledge-based. Some of the systems of this type are not knowledge-based. If a system is knowledge-based, a vast amount of knowledge is likely to be required to represent the possible states of the object, constraints, operations and the effects of their application, in order to provide as good a performance as that of a human expert of the domain. In addition, the knowledge representation method may be specific to the particular problem, such as "*shape grammars*" which represent geometric objects, or shape, for architectural design [Flemming, 1988].

(b) **Decision support systems** assist the users in a decision-making process. A system of this kind can take the advisory role of the domain experts by asking questions and interpreting the answers. In this sense, such a system can be used to preserve the expert knowledge regarding a particular decision-making process. For instance, a decision-making process within an organization (e.g. a design office), often requires expert knowledge, including "rules of thumb", which may be possessed by only its experienced members. As a knowledge-based decision support system has the capability of preserving their experience on a computer, it can assist those less-experienced to make adequate decisions by allowing them to utilise the expertise. Although such a system performs little 'problems-solving' activity, it could play a powerful role as an organizational aid to decision-making [Greenwell, 1989].

(c) **Consultation systems** perform the reasoning process to produce a diagnosis or report about an event. Given a particular set of symptoms, a system of this kind normally traces the problems back to a particular cause, or causes, through its reasoning process. One of the most important characteristics of such a consultation system is that it has to be able to justify its judgement by explaining its reasoning process, i.e. how the system has obtained a particular result, to the user. The development of a consultation system, therefore, requirers a large amount of work when developing its explanatory facilities.

(d) **Intelligent computer-aided instruction systems (ICAIS)**, or **intelligent tutoring systems (ITS)**, aim to develop and improve the user's ability to solve problems of a particular domain. In all forms of education and training, people do not learn by being told general principles but need practice in applying them to many individual problems. During the course of education or training with such an ICAIS, the system allows the user to demonstrate the same reasoning strategies as the experts in the particular domain. The knowledge about the use of these principles therefore needs to be made explicit. In order to provide effective training, i.e. to transfer the knowledge effectively, an appropriate user interface is required to provide decent communication between the system and the trainee, i.e. the user.

(e) **Intelligent front end (IFE)**, or **intelligent interfaces to a computer system**, are intended to help users exploit a computer software package to solve a particular problem. A user of a computer system or software package may find difficulties in using it because of:

(i) a lack of knowledge of the language or interface protocol through which the application package's functions can be invoked; and/or

(ii) a lack of understanding of the underlying concepts of the software packages.

In this sense, the effective use of an application software often requires a considerable amount of expertise. An IKBS could be used to improve the man-machine interface between the particular software and the user, by providing appropriate information, i.e. instructions and help, regarding the application software. In this case, an IKBS is closely coupled to the application software, and the domain knowledge of the IFE involves that of the application package's command language.

5.3 An IKBS for Inter-disciplinary Building Design Working

5.3.1 Motivation for the application of IKBS techniques

Application of IKBS techniques involves:

(a) *knowledge acquisition*: collecting and organising the knowledge regarding a particular domain, and

(b) *knowledge representation*: developing a knowledge-base, i.e. coding, or expressing, the knowledge explicitly using knowledge representation techniques, such as production rules (e.g. "*IF-THEN*" rules).

The IKBS approach may, therefore, imply that the object of the domain (i.e. building design process, for this project) is described in terms of sets of rules, or knowledge, so that the knowledge within the knowledge-base will be utilised through the inference process.

Such an approach was considered advantageous in this project when the computer-based design aid proposed in Section 5.1 was developed, because of the following reasons:

(1) <u>Features of the design process</u>

As discussed in Chapter 3, it is difficult to describe the design process in terms of a well-structured form, e.g. a mathematical model, because

- (i) the selection of design parameters appears to be a matter of a designer's expertise and design philosophy; and
- (ii) many of the relationships between the parameters are not clearly defined or understood.

Representing the process in terms of knowledge could be a powerful means to describe the building design process, because designers seem to possess the rules concerning the mapping of relationships between these parameters as a part of their expertise, although this understanding is often unconscious. If such expertise is acquired, the IKBS approach is a feasible methodology to cope with the sheer complexity of the design process than other more direct techniques, such as problem-solving via a mathematical relationship.

(2) Implementation of the framework for inter-disciplinary design working

The framework developed in Chapter 4 comprises the knowledge regarding inter-disciplinary building design working with particular reference to daylighting and lighting design aspects. In other words, the framework describes the building design process in terms of the relationships between design variables which are associated with itemised knowledge units. The application of IKBS techniques are considered suitable for implementing an inter-disciplinary design working framework, because it allows the knowledge to be expressed explicitly and, therefore, to be made available without a huge amount of pre-processing.

(3) Improvement of the system

An IKBS could be used to prevent dilution or loss of expert knowledge. But, inter-disciplinary building design working is open-ended, and, therefore, it may well be necessary to modify the knowledge so as to maintain the system's legitimacy. The IKBS approach would be advantageous to cope with such modification, since it describes knowledge in an explicit manner such as rules. Moreover, the introduction of new technologies into the building industry may result in the change of the design methodology. The separation of knowledge from the reasoning mechanism of the system allows the knowledge-base to be updated without the need to changing its reasoning facility. The system's capability could, therefore, be improved more easily than other systems formed in conventional computer programs, simply by adding and modifying these rules.

5.3.2 The domain of the IKBS for inter-disciplinary design working

A domain of an IKBS is the field, or scope, of knowledge or activity which the system is going to deal with. Developing an IKBS requires its domain to be specified and confined to a particular area of activities, so that the system can achieve its objectives with finite amount of knowledge. As a result, the domain of an IKBS tends to be discipline-specific so that the domain knowledge necessary can be acquired from a single human expert. The domain of an IKBS for artificial lighting design, for example, could be confined to only that design issue, as an artificial lighting designer's expertise may do.

Considering an IKBS for inter-disciplinary design working, the word "inter-disciplinary" may suggest more than one domain. How can the domain of such an IKBS be specified? The domain of the IKBS for inter-disciplinary design working is primarily considered as the inter-relationships between the design activities involved in various design issues, each of which may be discipline-specific. In this sense the knowledge associated with this domain may be possessed by a group of designers, i.e. design team, rather than individuals, in terms of their team working. For this project, the domain was interpreted as:

(a) how to work though the design process, and

(b) what to do in relation to each design activity.

The framework developed in Chapter 4 describes:

(a) "how to work" in terms of a logical sequence of design activities, and

(b) "what to do" in terms of cross-references, i.e. design criteria and potential conflicts regarding each design decision.

In other words, it was considered that the framework was capable of accommodating the domain for inter-disciplinary design working, although the knowledge was extracted from published materials, rather than a design team.

5.3.3 Functions of an IKBS for inter-disciplinary design working

It was decided to develop an IKBS for inter-disciplinary building design working based upon the framework developed in Chapter 4. Having considered the IKBS in relation to the objectives discussed in Section 5.1, its functions were identified as follows:

(1) Demonstrating inter-disciplinary building design working

The *primary function of the IKBS is to* demonstrate inter-disciplinary building design working by implementing the framework. In other words, the system allows the user to follow the logical sequence of the design activities, taking account of the cross-references.

(2) Providing the guidance for inter-disciplinary building design working

The IKBS provides the users with appropriate guidance, i.e. explanation and directions, regarding inter-disciplinary building design working, so that they can improve their understanding of the design process. To do this, the system has to have a human-computer interface (HCI) which is capable of presenting relevant knowledge and other information in an accessible form. If it has adequate 'explanatory facilities', such an IKBS can be used for training or educational purposes to promote inter-disciplinary design working.

(3) Checking the design process

The IKBS can also act as a 'process checker' by undertaking multilateral checking based upon the cross-references during the course of the design process. In other words, if the user has missed a vital issue to consider, or has made an inadequate design decision during the process, the system detects it through multilateral checking and gives him or her caution or warning, so that the errors of omission can be reduced.

(4) Providing extensive design data

Having a data-base containing design information which can be found in a written material, such as the CIBSE *Code for Interior Lighting*, the IKBS can allow adequate design data to be obtained at appropriate stage without time-consuming search. In this sense, the system could be an information resource which aids extensive use of design information.

(5) Automatic decision-making

The IKBS may automate low-level decision-making procedures, e.g. deciding target illuminance in relation to the activities carried out, so as to improve the productivity of the design process. However, care must be taken when introducing any level of automation of the process not to alienate the users by making them feel that they have no control or are redundant.

The next chapter explains the development of such an IKBS as well as the techniques used.

Chapter 6

Chapter 6

DEVELOPMENT OF A PROTOTYPE INTELLIGENT KNOWLEDGE-BASED SYSTEM FOR INTER-DISCIPLINARY BUILDING DESIGN WORKING

This chapter explains the development of a prototype intelligent knowledge-based system (IKBS), as well as the IKBS techniques used. Section 6.1 explains the objectives and outline of the development process of the prototype system. Section 6.2 describes the IKBS techniques i.e. knowledge representation and inference mechanism, employed to develop the prototype system, in terms of the use of a commercially available expert system shell, *Leonardo* 3. The user interface for the prototype system is discussed in relation to the facilities provided by *Leonardo* 3, in Section 6.3. In Section 6.4, the design of the prototype system is explained in terms of its hierarchical knowledge-base structure. Then, the operations of the prototype system are described in Section 6.5, and the capability of the developed system is assessed in Section 6.6, in relation to the functions required of a computer-based design tool of this kind.

6.1 Introduction

6.1.1 Development of a prototype system

This project aims to promote inter-disciplinary design working and effective use of information via intelligent knowledge-based system (IKBS) techniques. For this purpose, a framework for inter-disciplinary building design working was developed in Chapter 4, with particular reference to daylighting and lighting design aspects. Having discussed the application of IKBS techniques in terms of its domain and functions in Chapter 5, it was decided to develop an IKBS, based upon this framework. Consequently, a prototype system was constructed using a commercially available expert system shell, *Leonardo* 3.

The prototype IKBS was primarily intended to implement the framework so that inter-disciplinary building design working support could be demonstrated. In addition, it was designed to provide the functions which were discussed in Section 5.3. The prototype system was therefore evaluated in terms of these functions, to assess the viability of the IKBS techniques. Such a prototype system may be used for further study regarding the application of IKBS to the building design process, aiming at an integrated design environment, for example.

6.1.2 Use of *Leonardo* 3

The prototype system was constructed using a commercially available expert system shell, *Leonardo* 3, which was developed by *Creative Logic* Ltd. *Leonardo* 3 provides system developers with the editors which facilitate the development of a knowledge-base, and an inference mechanism with explanation functions which enable the users to trace the reasoning process that has taken place. An IKBS can, therefore, be constructed by developing only a knowledge base which is specific to the application. *Leonardo* 3 also provides user interface facilities. A system developer may employ its default screen, or develop more sophisticated interface screens using these facilities. The system developer could save a great deal of time and effort when implementing an application on a computer, by making use of these pre-provided functions and facilities, instead of writing a program in a computer language such as *LISP* or *PROLOG*. In other words, the use of *Leonardo* 3 may help a reasonable application system to be developed in terms of both its knowledge-base and user interface.

The use of an expert system shell, however, may often restrict the capability of the developed application within its own technical scope. Having considered the facilities of *Leonardo* 3 by undertaking a trial use, it was found that *Leonardo* 3 could be a powerful tool to develop a prototype system. It was, therefore, considered that the use of *Leonardo* 3 would be advantageous for this particular project. The functions of *Leonardo* 3 will be explained briefly in Section 6.2 and 6.3. The developing techniques associated with the use of *Leonardo* 3 will described in Section 6.4.

6.1.3 Development plan

As mentioned in Chapter 5, the process of developing an IKBS can be divided into two stages, i.e.

(a) "*knowledge acquisition*", which implies obtaining expert knowledge and organizing it; and
(b) "*system development*", which involves coding the knowledge within a knowledge-base, as well as providing an appropriate user interface.

In the context of developing an IKBS, the development of a framework for inter-disciplinary building design working, described in Chapter 4, can be regarded as knowledge acquisition. Having developed the framework, the system development using *Leonardo* 3 was carried out in the following four phases:

(1) understanding the functions and capability of *Leonardo* 3,
(2) system design,
(3) system implementation using *Leonardo* 3, and
(4) system evaluation.

The relations between these phases and the developed framework are illustrated in Figure 6.1. Each of these phases is outlined below.

(1) Understanding the functions and capability of *Leonardo* 3

The functions of *Leonardo* 3 and its potential capability had to be understood, in terms of its knowledge representation techniques, inference mechanism, and user interface development facilities, before starting the system development process. For this purpose, a previous project involving the use of *Leonardo* 3 [Charalambopoulos, 1992] was reviewed, and a trial use of this tool was undertaken. The functions of *Leonardo* 3 are briefly explained in relation to its knowledge representation techniques and user interface facilities, in Section 6.2 and 6.3, respectively.

(2) System design

The system structure of the prototype, i.e. the knowledge-base as well as user interface, were specified, taking account of the functions to be accomplished, as well as the potential capability of *Leonardo* 3. The knowledge-base of the prototype system was designed in a hierarchical structure in accordance with the rational description of design work comprising *design issues* and *design tasks*, which was defined in Section 4.2 of Chapter 4. The system design is described in detail in Section 6.4.

(3) System implementation using *Leonardo* 3

The system design was put into practice using *Leonardo* 3. Here, "modularization" was one of the key concepts. The knowledge-base was considered to comprise "modules" each of which represents a collection of design work, i.e. *design issues* and *design tasks*. These modules were nested as the hierarchy of the design work was accomplished. Subsidiary knowledge-bases and user interface screens were then developed within these modules. The prototype system was finally developed by integrating these modules into an entire system using the *Merge* facility of *Leonardo* 3. The operations of the prototype system are described in Section 6.5.

(4) System assessment

The capability of the prototype system was assessed, in terms of the functions required for the design tool, in order to evaluate the viability of the IKBS techniques. This is discussed further in Section 6.6.

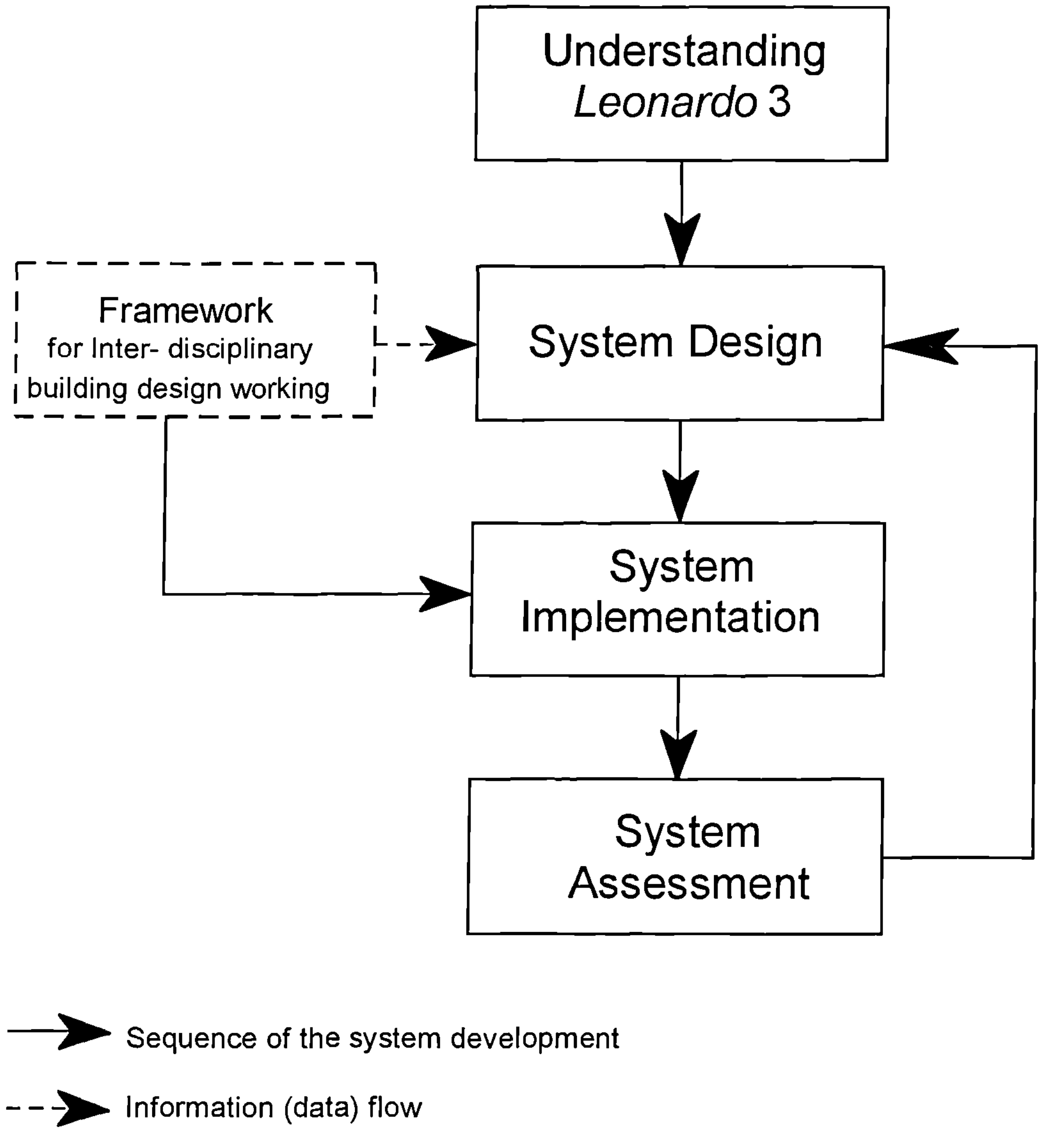


Figure 6.1 Four phases of developing the prototype system

6.2 Intelligent Knowledge-Based System Techniques

This section aims to provide an understanding of the knowledge representation and inference mechanism in terms of the use of *Leonardo* 3. (*Leonardo* 3 will be described as "*Leonardo*" in the rest of this chapter, unless particularly stated.) In *Leonardo*'s knowledge-base, knowledge is represented by a set of "**if-then**" rules, which are known as *production rules*, and utilised through an inference mechanism. Section 6.2.1 explains a production rule as well as the elements composing it, such as objects and operators. Section 6.2.2 briefly explains the *Leonardo* knowledge-base in terms of the *RuleSet*, *objects* and *object frames*. Then, Section 6.2.3 explains two types of inference mechanisms, i.e. forward chaining and backward chaining, and describes *Leonardo*'s default reasoning method and relevant functions.

6.2.1 Production rules

(1) A production rule

Knowledge can be described as a set of "**if ... then ...**" rules, which are known as *production rules*. A production rule is a conditional expression of the general form:

if *condition* **then** *result*

or

if *condition* **then** *action*

The first form can be interpreted as "if the *condition* is true, then the *result* is true," or "in order that the *result* is true, the *condition* must be true." The second form may be understood as "if the *condition* is true, then do the *action*." The *condition* is a clause of some kind which is tested to see whether or not it is true. The *condition* clause may be called the *antecedent* of the rule. The second part of the rule, i.e. the *result* or *action*, can be called the *consequent* of the rule. Then, the basic syntax of a production rule can be described as:

if *<antecedent>* **then** *<consequent>*

An example of a production rule may be:

<u>*example 1*</u>

if *x* is *val1* **then** *w* is *val5*

In this example, the *antecedent* "*x* is *val1*" is evaluated to see whether it is 'true' or 'false' during the reasoning process. If it is true, then the rule "fires" and the *consequent* of the rule, i.e. "*w* is *val5*" is executed.

(2) *Antecedent* clause

An *antecedent* clause comprises an *object* and a *value*, or another *object*, linked by an *operator*. The general syntax of an *antecedent* clause is:

if *<object>* *<operator>* *<object / value>*

An *object* is a logical item to which a name as well as value and/or other information may be assigned. Such an object may be called a "*value carrying object*". The *value* retained by an object may be called "*object value.*" An *object value* may be a number, some text, or a list of text items. The *operator* defines the relationship between the object on its left and the value on its right, which must be true for the *antecedent* clause to be true. Considering the *example 1* shown above, "*x*" is an object, "is" is an operator, and "*val1*" is a value. In this example, if, and only if, the object "*x*" has already the value "*val1*" as its object value, is this *antecedent* clause true.

The *antecedent* of a rule may have multiple clauses joined by the conjunctions "**and**" and "**or**":

if *<antecedent clause* 1>
and/or *<antecedent clause* 2>
and/or ...
then *<consequent clause>*

For instance,

<u>*example 2*</u>

if *x* is *val1*
and *y* is *val2*
then *z* is *val3*

Here, these **and** and **or** can be regarded as the logical operators, "AND" and "OR", respectively. To describe the negation of an *antecedent* clause, the word **not** may be used. For example,

<u>*example 3*</u>

if *x* is not *val1*
and *y* is not *val2*
then *z* is *val4*

The use of the negator **not** is equivalent to the logical operator "NOT". Therefore, the *antecedent* of the rule with multiple clauses can be regarded as a logical equation comprising more than one statement.

(3) *Consequent* clause

When the *antecedent* of a rule is found to be true, its *consequent* clause is executed. Considering *example 1* again, the value *val5* will be assigned to the object "*w*", if the antecedent clause is found to be true (i.e. if the object value of the object "*x*" is "*val1*"). The general syntax of a *consequent* clause is:

then <object> <operator> <object / constant / expression>

By executing a *consequent* of a rule, *Leonardo* can carry out several different things, for instance:

- assigning values to objects which can then be used by other rules;
- asking for a value for an object;
- displaying an object value;
- invoking an input or output screen; and
- executing a *Leonardo* or external procedure.

Leonardo allows the *consequent* of a rule to have multiple clauses, separated by semi-colons, as shown below:

if *<antecedent clause>*
then *<consequent clause* 1>;
<consequent clause 2>;
...
<consequent clause n>

Detailed explanation about the syntax of both *antecedent* and *consequent* clauses can be found in the *Leonardo User's Guide,* Chapter 4 [1989].

6.2.2 *Leonardo* knowledge-base

Knowledge may eventually be described by a set or sets of rules. The design concept of *Leonardo* is, however, to think of a knowledge-base as being comprised of sets of rules, "*RuleSets*", instead of thinking of the system as being composed of rules. A *Leonardo* knowledge-base is comprised of the *Main RuleSet,* objects and object frames. Figure 6.2 illustrates the structure of a *Leonardo* knowledge-base.

(1) *Main RuleSet*

The *Main RuleSet* is the basic component of the knowledge-base. Every application starts with the *Main RuleSet.* A *Main RuleSet* is a free format list of production rule statements. It may contain not only production rules, but also other kinds of rules, called *assertive rules,* which do not require an "if-then" construction. The following five assertive rules are available:

(a) **ask** <object>
to force *Leonardo* to ask the user for the value of its associated object;

(b) **say** <object>
to force *Leonardo* to output the value of its associated object once it becomes known;

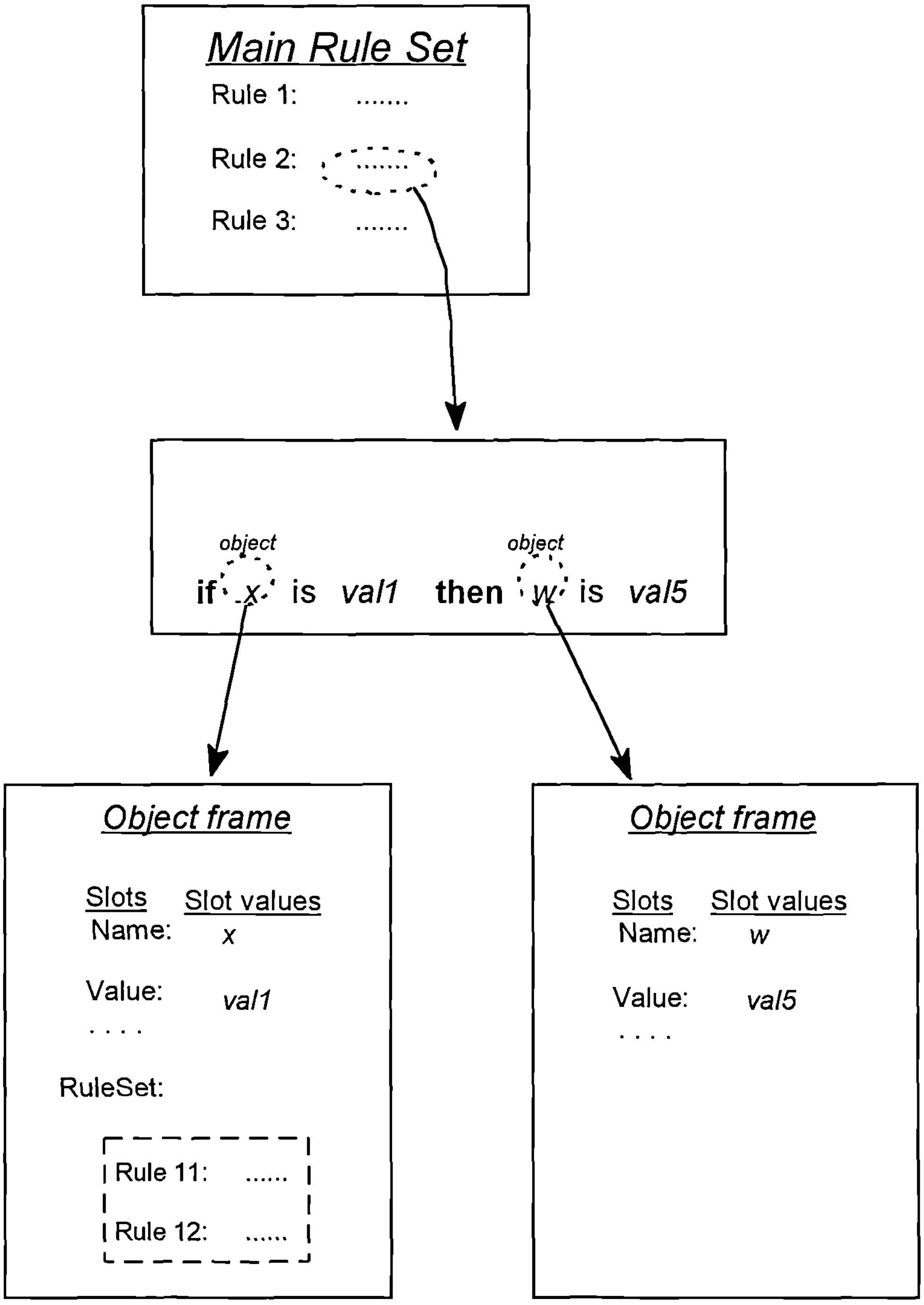


Figure 6.2 Structure of a *Leonardo* knowledge-base: *Main Rule Set*, *objects* and *object frames*.

(c) **use** <screen object>

to invoke a screen at the beginning of execution.

(d) **seek** <object>

to instruct *Leonardo* as to the object whose value is the target of the whole set of rules (this rule will be explained in relation to inference mechanism in Section 6.2.3); and

(e) **control** <option>

to establish global control parameters on the knowledge-base.

(2) Value carrying objects, object values, and operators

Leonardo uses different types of value carrying objects, i.e. *Real*, *Text* and *List*. In accordance with the object type, the *object value* is either a number (for *real* objects), some text (for *text* objects), or a list of text items separated by commas and surrounded by quotes (for *list* object). The type of a value carrying object is governed by the operator that is used to relate it to its value. The following operators may be applied:

(a) The operators available for use in antecedent clauses with *real* objects are:

=, <=, <, >=, >, and <>.

(b) For *text* objects in antecedent clauses, *Leonardo* uses the *text operators* **is** or **are**.

(c) The operators available for use in antecedent clauses with *list* objects are:

include/includes, exclude/excludes, equiv, overlaps

(d) To negate a text or list operator, *Leonardo* allows the word "**not**" to be used in a rule antecedent (see *example 3* in Section 6.2.1). When used with a list operator, the words **does** and **do** can be added to make the rule more readable. They are ignored by the system when antecedents are evaluated, and as a result, a system developer can write rules in clauses which resemble English sentences. The "**not**" operator is not permitted in the consequent portion of a rule.

(3) *Object frames*

All value carrying objects have a name and a value. There will be much more information to be associated with a given object than its name and value, however. *Leonardo* provides for the storage of this information in a structure known as an *object frame*. Each *value carrying object* may have *an object frame* which is associated with an object by name - the *object frame* and the *object* have the same name. An *object frame* can be regarded simply as a data structure which is designed to contain the additional information relating to an object. The *object frame* is comprised of *slots*, which may have values to describe the attributes of the object. The *slots* and their values are used to store information about the object. They may also be used to control the methods of value derivation, query screens and display screens. For further information about *Leonardo object frames* in general, see the *Leonardo User's Guide*, Chapter 5 and 6; a complete reference on each slot can be found in the *Leonardo Reference Manual*, Chapter 3.

(4) Multiple *RuleSet* systems

One of the most powerful features of an *object frame* is a slot called "*RuleSet*". This *slot* is an additional slot which each value carrying object can have within its object frame, and contains a set of rules (*RuleSet*) which are used to derive the value of the object. The *RuleSet* is only considered when a value for the object is required. The rules in a *RuleSet* slot follow the same format as in a *Main RuleSet*. These rules may use objects which themselves have a *RuleSet* in their *RuleSet* slots. This is called a "*multiple RuleSet system*". The *multiple RuleSet system* has the following benefits:

(a) The overall structure of the system is clearer, as this feature encapsulates the rules which derive the value of an object. As a result, a *Leonardo* knowledge-base can be developed in a well-organised manner.

(b) Knowledge which is relevant to the achievement of some sub-goal of the system is related explicitly to that sub-goal. Thus, on-going maintenance of the knowledge base is eased.

(c) It is easy to copy them to another knowledge-base, since *RuleSets* are discrete components within a knowledge base.

(d) Faster compilation, and more efficient execution of a structured system. The reasoning strategy involving the multiple *RuleSet* is explained in Section 6.2.3, (7) *Extended backward chaining*.

Use of this facility for the prototype system will be described in Section 6.4 in relation to the system design and implementation of the prototype system. Further description can be found in Chapter 10 of the *Leonardo User's Guide*.

(5) Other kinds of objects

Leonardo may have different kinds of objects other than *value carrying objects*. They are *procedure objects*, *screen objects*, and *class* and *member objects*, and each of these objects has its own type of associated *object frames*.

(a) *Procedure objects*

Procedure objects contain procedural codes which may be executed from several points during knowledge-base execution. More information about the procedure is in Chapter 9 *Leonardo User's Guide*, a complete reference of each procedural language command can be found in Chapter 4 of *Leonardo Reference Manual*.

(b) *Screen objects*

Leonardo provides a tool, called "*Leonardo Screen Designer*", for designing input and display screens. *Screen objects* are these screens which have been generated using the *Screen Designer*. Use of the *screen objects* will be explained further in Section 6.4, in relation to the user interface of the prototype system. More detailed information regarding the *Leonardo Screen Designer* screen can be found in the *Leonardo User's Guide* Chapter 14 and 15.

(c) *Class and member objects*

Class and member objects can be used to accomplish the inheritance between objects. Here, a *class object* may have instances, which are the concrete examples of the *class*. For example, "poodle" and "scottish terrier" are the *instances* of the *class* "dog". The *member objects* represent these instances, and are associated with the *class object*. In other words, the *class object* is considered as the "parent" object of these associated *member objects*. Their *object frames* contain information about the objects and their relationships between the class and members. The *class object frame* may contain slots defined by the system developer to describe important attributes of the object; each of the *member object frames* inherits these attributes from its parent object. Further explanation can be found in the *Leonardo User's Guide* Chapter 10 and 11.

6.2.3 Inferencing mechanism

An IKBS utilises knowledge described in a set of rules through a reasoning process. There are two distinctive inference mechanisms which are most commonly used for reasoning with production rules. They are *forward chaining* and *backward chaining*.

(1) *Forward chaining*

Forward chaining is sometimes called "*data-driven reasoning*", because a system starts its inferencing process with the known data and reasons forward with that data as far as possible. To do this, the system begins by testing each rule and firing every rule whose antecedent can be shown to be true. As a result of this, more data are generated; and the system then tests the rules again using the newly produced data. The system performs this process iteratively until no more rules fire.

For example, let us consider a set of rules shown in *example 4*:

example 4

Rule 1: **if** *x* **is** *val1*
and *y* **is** *val2*
then *goal* **is** *done*

Rule 2: **if** *x1* **is** *val3*
then *x* **is** *val1*

Rule 3: **if** *y1* **is** *val4*
then *y* **is** *val2*

Rule 4: **if** *x* **is** *val1*
then *w* **is** *val5*

To start the *forward chaining* inference, some data are required. Let us assume that the data to start with are:

x1 = *val3*
y1 = *val4*

Then, the process will be undertaken as follows:

[Pass 1] Rule 2 fires, *x* is instantiated as *val1*;
Rule 3 fires, *y* is instantiated as *val2*.
[Pass 2] Rule 4 fires, *w* is instantiated as *val5*;
Rule 1 fires, *goal* is instantiated as *done*.
[Pass 3] No rules fire, inference process is completed.

The word "instantiated" was derived from the *Leonardo User's Guide*, and means that a particular value for an object has been established. At the end of the process, the following results have been obtained:

x = *val1*
x1 = *val3*
y = *val2*
y1 = *val4*
w = *val5*
goal = *done*

(2) *Backward chaining*

Backward chaining is called "*goal-directive reasoning*". As the name implies, the system establishes a target solution (goal), and tries to find evidence to prove it. In order to do this, first the system searches the knowledge-base for rules which might give the desired conclusion, i.e. the goal appears in the consequent of these rules. Then, the system examines the antecedents of one of these rules to see whether or not it can fire.

If the rule fires, the goal has been proven. If not, mostly this is the case, the *backward chaining* begins. The rule which the system has been working on is then put aside, or *stacked*, and a sub-goal is set up that is to provide the antecedent of the rule. Now, the system searches the knowledge-base for rules which can prove the sub-goal (i.e. those which include the sub-goal as their consequent). Once again the system examines the antecedents of the rules to prove them, and repeats the process of stacking rules and resetting its sub-goal until the process reaches the point where no rules can be found to provide the current sub-goal. At this point, the system is eventually forced to seek other means of deriving a value for, or *instantiating*, the current sub-goal. Generally the system queries the user for the value of the current sub-goal. Having received an answer from the user, the system returns to evaluating the last rule, i.e. *unstacks* it, and proceeds in the same fashion.

Notice a major difference between forward and backward chaining. In the *forward chaining* all the known data were assumed at the beginning of the process, and the system did not question the user. In the *backward chaining*, on the other hand, no data were assumed, and the system only asked for the information which is necessary to prove the direct line of reasoning.

Meanwhile, *backward chaining* can occur in two ways: *breadth-first* or *depth-first*. *Breadth-first backward chaining* tries all rules which might derive a value for the current sub-goal before re-establishing a sub-goal on any antecedents. *Depth-first backward chaining*, on the other hand, re-establishes a sub-goal on the antecedent of the current rule under consideration before trying any other rules. An example of *depth-first backward chaining* is shown below using the set of rules in *example 4*. Let us assume that we are trying to find a value for the object "*goal*". The reasoning process proceeds as below:

Try Rule 1: Need to find *x*;

Stack Rule 1; set a sub-goal on *x*.

Try Rule 2: Need to find *x1;*

No rule, query user: *x1* is instantiated as *val3* by user input.

Rule 2 fires: *x* is instantiated as *val1*.

Unstack Rule 1: Need to find *y*;

Stack Rule 1; set a sub-goal on *y*.

Try Rule 3: Need to find *y1;*

No rule, query user: *y1* is instantiated as *val4* by user input.

Rule 3 fires: *y* is instantiated as *val2*.

Unstack Rule 1:

Rule 1 fires: *goal* is instantiated as *done*.

At the end of the process, we know that:

$x = val1$
$x1 = val3$
$y = val2$
$y1 = val4$
$goal = done$

Notice that *w* was not instantiated because it was not in the line of reasoning.

(3) Inferencing in *Leonardo*

The standard method of inferencing in *Leonardo* is "*backward chaining* with opportunistic *forward chaining*", which is a combination of the two methods discussed above. Its basic inferencing mechanism is the *depth-first backward chaining*. When an object is instantiated, either through a rule or user query, however, the *forward chaining* is triggered. Such an opportunistic *forward chaining* enhances the effective use of the new data. After forward chaining is completed, backward chaining resumes. *Leonardo* also triggers forward chaining at the onset of inferencing to make maximum use of any data available at start-up.

Let us consider an example of this inference mechanism using the same rule set shown in *example 4*. Assume that we are trying to find a value for the object "*goal*". The reasoning process proceeds as follows:

Try Rule 1: Need to find *x*;

Stack Rule 1; set a sub-goal on *x*.

Try Rule 2: Need to find *x1*;

No rule, query user: *x1* is instantiated as *val3* by user input.

Rule 2 fires: *x* is instantiated as *val1*;

Rule 4 fires: *w* is instantiated as *val5*.

Unstack Rule 1: Need to find *y*;

Stack Rule 1; set a sub-goal on *y*.

Try Rule 3: Need to find *y1;*

No rule, query user: *y1* is instantiated as *val4* by user input.

Rule 3 fires: *y* is instantiated as *val2*.

Unstack Rule 1:

Rule 1 fires: *goal* is instantiated as *done*.

The process is basically as described for backward chaining; however, each time an object is instantiated the *forward chaining* is applied through the rules. The effect of this is that after Rule 2 fires: the *forward chaining* was applied based upon the object *x* instantiated as *val1*, and, as a consequence, Rule 4 fires which instantiates the object *w* as *val5*. At the end of the process, we know that:

x = *val1*
x1 = *val3*
y = *val2*
y1 = *val4*
w = *val5*
goal = *done*

Further information regarding *Leonardo* inference mechanism can be found in the *Leonardo User's Guide*, Chapter 6, 10 and 12.

(4) The *Seek* directive

All *Leonardo* knowledge-bases need a goal. The *Main RuleSet*, therefore, has to have a special rule which defines the objective of the knowledge-base. This is the **seek** directive. When *Leonardo* executes a knowledge-base, it literally seeks for a value for the object named in the **seek** rule. The **seek** rule can appear anywhere in the *Main RuleSet*, though it is often convenient to use it as the first rule. The **seek** directive is never used as a consequent of another rule, and is never used in *RuleSet* slots.

(5) *Backward chaining* candidates

Backward chaining works for *Real*, *Text* and *List* objects, but the object to trigger *backward chaining* must be in the last consequent clause.

<u>*example 5*</u>

```
        if      data    is      done
        then    sub-goal1       is      done;
                sub-goal2       is      done
```

In *example 5*, for instance, *backward chaining* will be triggered to this rule only if *sub-goal2* is the object which needs a value. If *sub-goal1* needs a value, this rule will not be considered, although *sub-goal1* will be assigned a value if the rule is fired.

(6) Order of value derivation

In order to derive a value for an object, *Leonardo* executes its process in the following order:

(i) *FixedValue* slot

A *value carrying object* may have a particular fixed value by setting it in the *FixedValue* slot within its associated object frame. At the onset of execution, all objects with a *FixedValue* slot are set to the value in the slot.

(ii) *Main RuleSet*

All **ask** and **use** assertive rules are executed in the order in which they appear in the *Main RuleSet*. Then, the forward inferencing proceeds until no further rules fire. Having completed this forward chaining process, *Leonardo* applies the depth-first backward chaining opportunistic *forward chaining* to the goal object (**seek** object), as described earlier. All rules within the *Main RuleSet* are scanned, first to last, for those which will derive the exact value required for the object. If none of these rules succeed, all rules are scanned for those which will derive any value for the object.

(iii) *RuleSet* slot

If no rules exist which can derive a value for the object, or if no rules fire (i.e. the antecedents are found false), *Leonardo* looks in the frame of the object for alternate methods of finding a value. The first slot of interest is the *RuleSet* slot. The reasoning process involving the *RuleSet* within a *RuleSet* slot is explained later in (7) *Extended backward chaining.*

(iv) *ComputeValue* slot

If there is no *RuleSet* slot within the object frame, the next slot for which *Leonardo* searches is the *ComputeValue* slot, which may have the name of a procedure to invoke in order to derive a value to the object.

(v) User query

If there is still no value obtained, *Leonardo* will query the user. *Leonardo* can be told not to query the user by making the value of the *QueryPrompt* slot of the associated object frame "*never*".

(vi) *DefaultValue*

If the user answers *unknown* or the *QueryPrompt* has been set "*never*", the value in the *DefaultValue* slot is used. If there is no default value, the system terminates the process and returns the message: "I am unable to draw any conclusions on the basis of the data."

(7) Extended Backward Chaining

As mentioned above, a set of rules (*RuleSet*) within the *RuleSet* slot are considered as an extra step in the value derivation process. For example, when a rule antecedent clause:

if object_x **is** value_x

is being evaluated within the *Main RuleSet*, and the value of *object_x* is not known, *Leonardo* searches for a rule consequent clause:

. . . **then** object_x **is** value_x

If no such rule is found, and there is also no rule available which derives any other value for *object_x* within the *Main RuleSet*, *Leonardo* looks in the frame for *object_x*, and performs the actions for deriving a value based on the information in the slots. In particular, if there is a *RuleSet* slot in the frame, the rules contained in the slot (subsidiary *RuleSet*) are loaded into memory and executed before trying the other methods. This is referred to as *extended backward chaining*.

When the subsidiary *RuleSet* is loaded, the activity in the previous *RuleSet* (in this case, it is the *Main RuleSet*) is halted, and the status of the execution of the old *RuleSet* is stored. (This is often referred to as *stacking* the previous *RuleSet*.) Then, the focus of attention of the system switches to this new *RuleSet*. When an object requires a value to complete the value derivation within the *RuleSet* slot, the same process will proceed, and if the object has a *RuleSet*, the current *RuleSet* will be stacked and the control of reasoning will again shift to the new subsidiary *RuleSet*. In fact, *RuleSets* may be nested up to 10 levels deep in this manner. It is important to note that subsidiary *RuleSets* will be searched for applicable rules, whereas *RuleSets* which are stacked will not be searched.

6.3 User Interface

The functions required for the computer-based design aid for inter-disciplinary design working include: presenting information in relation to a particular design activity, as well as process checking, as discussed in Section 5.3. These functions involve communication between the user and the IKBS via user interface screens. In order to achieve efficient use of the IKBS techniques, an appropriate user interface is crucial. In this section, firstly the user interface of the IKBS for inter-disciplinary design working is discussed in terms of six categories with some design guideline, and, secondly, the potential user interface capabilities of *Leonardo* are briefly explained.

6.3.1 User interface categories

The communication takes place in both directions: i.e. "from user to system", and "from system to user" (Figure 6.3). The former may be data entry by the user. The latter involves displaying information, screen prompts, alerts and warnings, help, and explanation regarding the system's reasoning process.

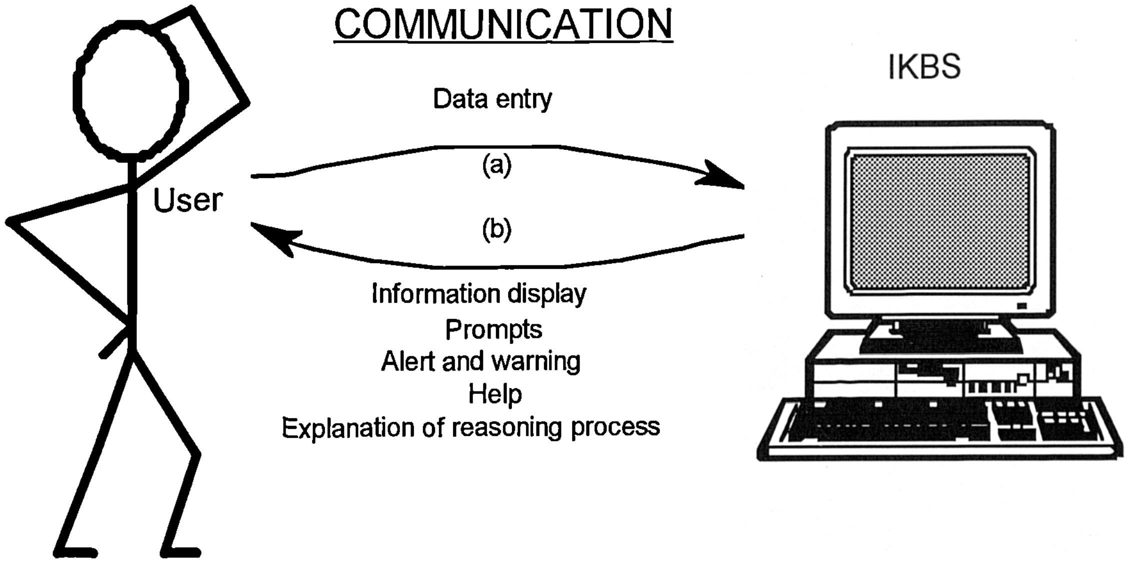


Figure 6.3 Communication between the user and the IKBS:
(a) from the user to the IKBS, and
(b) from the IKBS to the user.

Considering the functions required for the IKBS for inter-disciplinary design working, its user interface should be developed in terms of the following categories:

(1) information display
(2) prompts or directions
(3) data entry
(4) alerts and messages
(5) on-line help
(6) explanation of reasoning process.

Some guidelines about designing these interface functions are shown below.

(1) Information display

As an information resource, the IKBS may present an enormous amount of complex information, e.g. working guidelines and design data, to the user via its interface screens. The information display can take place in various forms such as text, tables, menus and graphics. The way in which the information is presented, and the interface style, will contribute to the usability of the system. McGraw [1992, p.135 -136] suggests that the ability of normal data displays to communicate effectively with the user is, in part, determined by:

- how the text or graphic is constructed;
- whether the words or objects are tied to the real world in which the user works; and
- the user's expectations.

When designing user interface screens, therefore, screen designers must consider how the user will process the information presented [McGraw, 1992, p.127]. Hence, information should be displayed on formatted screens, on which the user will search and selectively encode parts of the display, as opposed to reading a narrative display. Grouping similar items helps the user to organise information, and improves their readability. The items should also be arranged so that the display format minimizes layout complexity.

(2) Prompts or directions

The user interface is also responsible for communicating to the user directions as to the action that should be undertaken. Conveying directions often takes place in the form of screen prompts which tell the user what to do next. Prompts should leave no question about what the user is expected to do and how to respond. Some simple guidelines to develop effective prompt messages are as follows [McGraw, 1992, p.136-138]:

(a) *Recognition*

Prompts should appear in a position that makes them immediately recognisable. Most prompts appear in the centre of the screen.

(b) *Specificity*

Word choice and word position in a prompt sentence should be considered carefully. Choosing correct words to explain what the user needs to do is important. For example, "Press" should be used, instead of "Hit". The use of jargon has to be avoided. Action words, such as "Press", "Type" and "Select", should be placed at the beginning of the prompt, so that the user immediately knows what action is expected.

(c) *Consistency*

Once terminology is selected to describe a particular type of action, it should be applied consistently to the development of all screen messages throughout the system. In addition, the prompts should appear within the same format. The same layout should be used for type-in or menu-based data entries in relation to the screen prompts.

(3) Data entry

Data entry is the task of responding to screen prompts and feeding the user's decision or required data to the system. It may be accomplished by using menus or a type-in data entry style. Menus are a viable interface style for an IKBS, because they provide the user with a set of options and enable the system to be used by a wide range of users. Type-in entry is, on the other hand, usually not preferred due to the complexity of the problem for which the IKBS may have in interpreting such data input. *Leonardo* is capable of providing both types of data entry methods, but the menu-based data entry was employed as the primary method of the prototype system.

(4) Alert messages

The IKBS will undertake process checking in terms of inter-disciplinary design working. When the system detects an inappropriate action, alert messages should be raised to notify that the user has made an inadequate decision, given the current context, or seemingly forgotten an important step in the process. In this case, the alert messages should point out possible consequences of the user's inappropriate action, and may offer advice. In addition, alert messages should contain a user response signal, such as 'Cancel', 'Proceed', 'Continue' 'Stop', so that the user can control the system after recognising the alert.

(5) On-line help

An IKBS may include on-line help. On-line help provides messages that assist the user in accomplishing tasks, selecting among options, understanding the system, or understanding the terms and concepts used by the system. It is preferable that the help messages are context-sensitive. The help functions of the prototype system involve detailed directions as to how to use the system, and the descriptions of particular terms and concepts associated with inter-disciplinary design working.

(6) Explanation of reasoning process

Explanations provide information about why a particular question was asked or why a particular action is recommended by the system. This function gives the user a chance to see how rules or other contents of the knowledge-base are being to used to make decisions in the system. *Leonardo* provides for such an opportunity with the use of the function keys, as explained in relation to its inference mechanism in Section 6.2.

6.3.2 User interface facilities of *Leonardo* 3

For designing user interface screens, *Leonardo* essentially has four levels of screen design capabilities. At the most primitive level, default screens are generated automatically whenever an object value is requested. At a second level, the *frame slots* and *frame slot language* provide a quick method of specifying a formatted dialogue screen for a given object. (Further explanation about the *frame slot* and *slot language* can be found in *Leonardo User's Guide* Chapter 5.) The *Screen Designer* toolkit provides a third level of sophistication which allows a more flexible screen to be developed. Finally, for complete control of the screen process, the system developer has the option of developing absolutely tailored interfaces using the *Leonardo procedural language*.

For the interface screens of the prototype system, the first and third levels of user interface techniques, i.e. default screens and *Screen Designer* screens, were mainly employed.

(1) Default screens

The use of default screens allows the logical flow of the prototype system to be checked out and developed by the developer without devoting too much time to questions of input/output specification. The information which will be displayed in a default screen can be contained in the object frame associated with the value carrying object under question, although it is presented in a fixed layout. A prompt sentence can be specified in the *QueryPrompt* slot. The information related to the query can also be contained within the *QueryPreface* slot. In addition, further text information about the object contained in the *Expansion* slot is available during the query session. Further explanation about the default screens and object frame slots can be found in the *Leonardo User's Guide* Chapter 5.

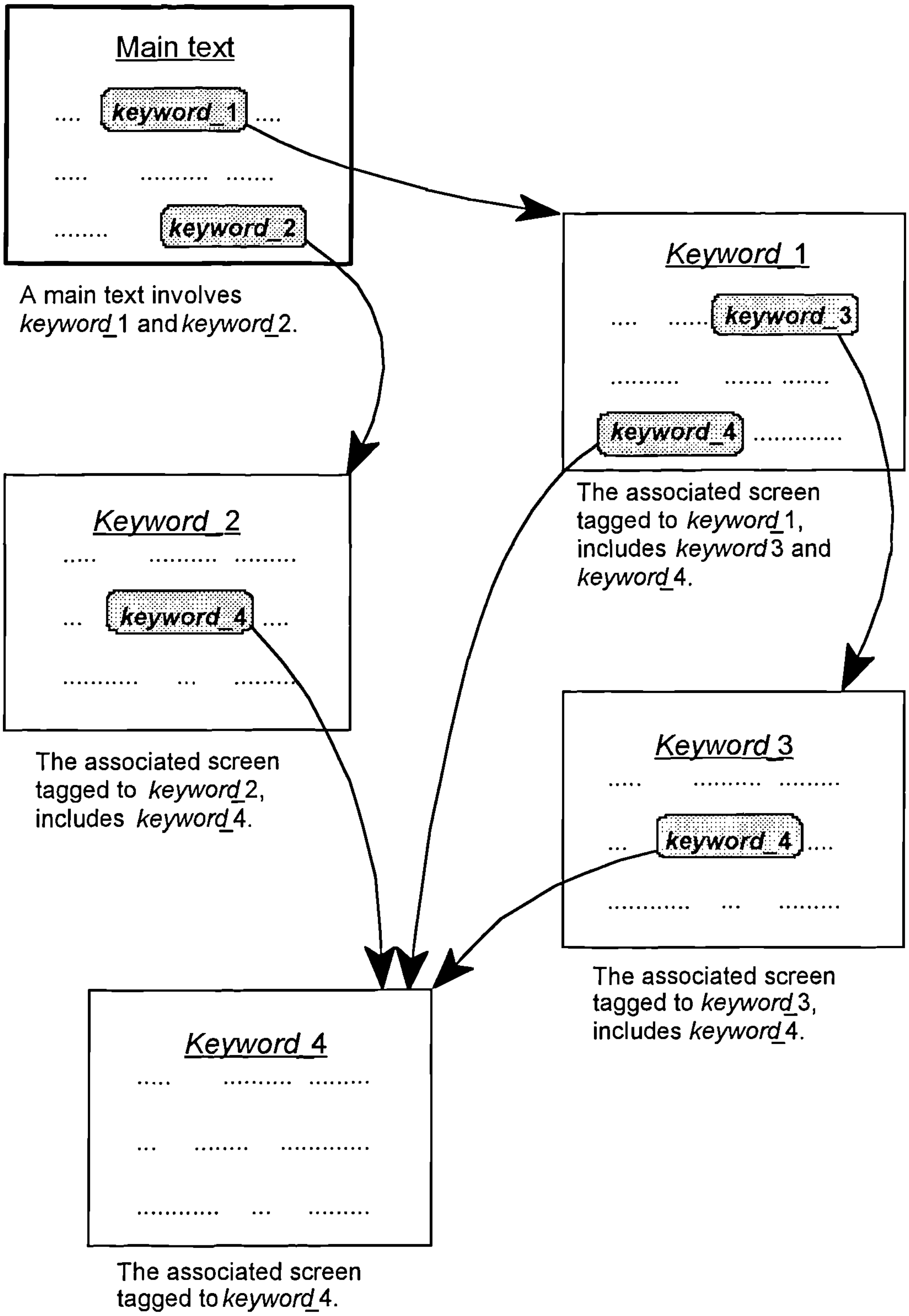
(2) The *Screen Designer* screens and the *hypertext* facility

The interface screens designed with the *Screen Designer* toolkit can be used for various purposes, e.g. displaying object values; handling multiple input fields on one screen;

defining multiple menus on-screen; providing an application-specific help screen; and providing *Hypertext* facilities. These screens are dealt with as *screen objects*, and can be called from rules and object frames.
The screens produced by the *Screen Designer* may provide application-specific help. Any screen display may have an associated screen, called the *LookAside Screen*, available by pressing the <F3> key while the current screen is being presented. This associated screen can be used to provide general descriptive help assisting the end-user in the requirements for filling in the current master screen. The *LookAside Screen* is sensitive to the values currently entered on the master screen, and thus the help provided can be tailored to address any likely errors that the user may have made. Help can also be provided at the level of individual fields on the screen, using the *Expansion* slot of the associated object. Pressing <F4> will pop up an overlaid window onto the screen, with information which is directly related to the current field. The *Leonardo User's Guide* Chapters 14 and 15 provide further detailed explanation about the use of the *Screen Designer* screens.

One of the powerful user interface facilities that *Leonardo* provides is the *hypertext* function. *Hypertext* is generally defined as the ability to provide non-linear textual documentation on a randomly accessible basis, with selection being keyed on words and phrases [*Leonardo Documentation supplement*, 1990]. Figure 6.4 is an example of a non-linear textual documentation structure of *hypertext*. A screen involving keyed words and phrases is presented to the user, who may then select a given key word or phrase and see the associated text displayed in another screen. (The associated screen displaying the associated text is called an *associated screen*.) The associated text in the associated screen will likewise provide a set of new available key words and phrases, from which the user may again select, or, alternatively, the user may go back to the previously displayed text panel and set off in a new direction based upon an alternative key word or phrase. Because of its non-linear documentation structure on a randomly accessible basis, the *hypertext* can be a powerful tool to display inter-related concepts. The associated screens of *Leonardo* will display only text fields and box markers. No input and output will be permitted, and any input/output fields will not be offered.

Neither will the background field be coloured. This means that screens may be set up which offer *hypertext* as an adjunct to their input processing, and the same screens may be pointed at from elsewhere to provide *hypertext* information without the Input/Output being triggered.



A main text involves *keyword_1* and *keyword_2*.

The associated screen tagged to *keyword_1*, includes *keyword_3* and *keyword_4*.

The associated screen tagged to *keyword_2*, includes *keyword_4*.

The associated screen tagged to *keyword_3*, includes *keyword_4*.

The associated screen tagged to *keyword_4*.

Figure 6.4 *Hypertext*: non-linear textual documentation structure

6.4 Design of the Prototype System

This section aims to provide some insight as to how the prototype system works as well as its design concepts. The prototype system is primarily intended to demonstrate inter-disciplinary building design working by implementing the framework which was developed in Chapter 4. The prototype system is comprised of sets of rules (*RuleSets*) which exercise the design process based upon the framework, and user interface screens. The *RuleSets* comprising the system's knowledge-base was developed using the *Multiple RuleSet* techniques to modularize them in accordance with the conceptual hierarchy of the building design process, upon which the framework was based.

Section 6.4.1 introduces the conceptual hierarchy of the building design process by reviewing Section 4.2 and 4.3, and describes the outline of the system's operation in relation to it. Section 6.4.2 explains the system development approach using the *Multiple RuleSet* technique in terms of modularized *RuleSets*, or *RuleSet* modules.

6.4.1 Hierarchical structure of the prototype system

(1) Conceptual hierarchy

Through the development of a rational description of the building design process (Section 4.2) and a framework for inter-disciplinary building design working (Section 4.3), the building design process is considered to comprise the following concepts:

(i) ***Design features***: having contemplated its ill-defined nature in Section 4.2, the building design process was considered to involve two features, i.e. "*briefing*" and "*development of a design solution*".

(ii) ***Design issues***, which were considered as sub-problems associated with the *design features*.

(iii) ***Design tasks***: sets of individual design activities which originate from a particular *design issue*. They were represented by *design variables* within the framework for inter-disciplinary design working developed in Section 4.3. It was considered that these design variables have a particular range of values which are achieved when *design tasks* are completed.

(iv) **Cross-references**, which recognise relationships between the *design variables* which represent the *design tasks* and the performance characteristics and allow these to be evaluated, in terms of *design criteria* and *potential conflicts.*

It is understood that these concepts constitute a hierarchy describing the building design activities as illustrated in Figure 6.5. Here, the *design features* are positioned at the top level, *Level* 1; the *design issues* derived from of the *design features* are at *Level* 2; the *design tasks* are ranked at *Level* 3 as they originate from a particular *design issue*; and the cross-references are placed at the bottom, *Level* 4. This hierarchical scheme of the concepts is the basis upon which the operation, as well as the knowledge-base, of the prototype system were designed and developed.

(2) Outline of the prototype system operation

As illustrated in Figure 6.6, the operation of the prototype system was developed in relation to the conceptual hierarchy. The prototype system was designed to operate as follows:

(i) the prototype system starts a session asking the user to determine which *design feature* is to proceed, "*Briefing*" or "*Development of a design solution*", at *Level* 1;

(ii) when a *design feature* is chosen, the system takes the user to *Level* 2, where the user may select a particular design issue of interest out of the *design issues* associated with the chosen *design feature*;

(iii) once a particular *design issue* has been selected, the system then leads the user through a sequence of the *design tasks* which originate from that selected *design issue* at *Level* 3;

(iv) as these *design tasks* are being carried out, the process checking may be undertaken for every *design task* based upon the cross-references at *Level* 4; and

(v) when the design process regarding the selected *design issue* is completed, the user may either continue the session by choosing a new *design issue* of interest, or quit the process.

The operation of the prototype system will be explained further in Section 6.5.

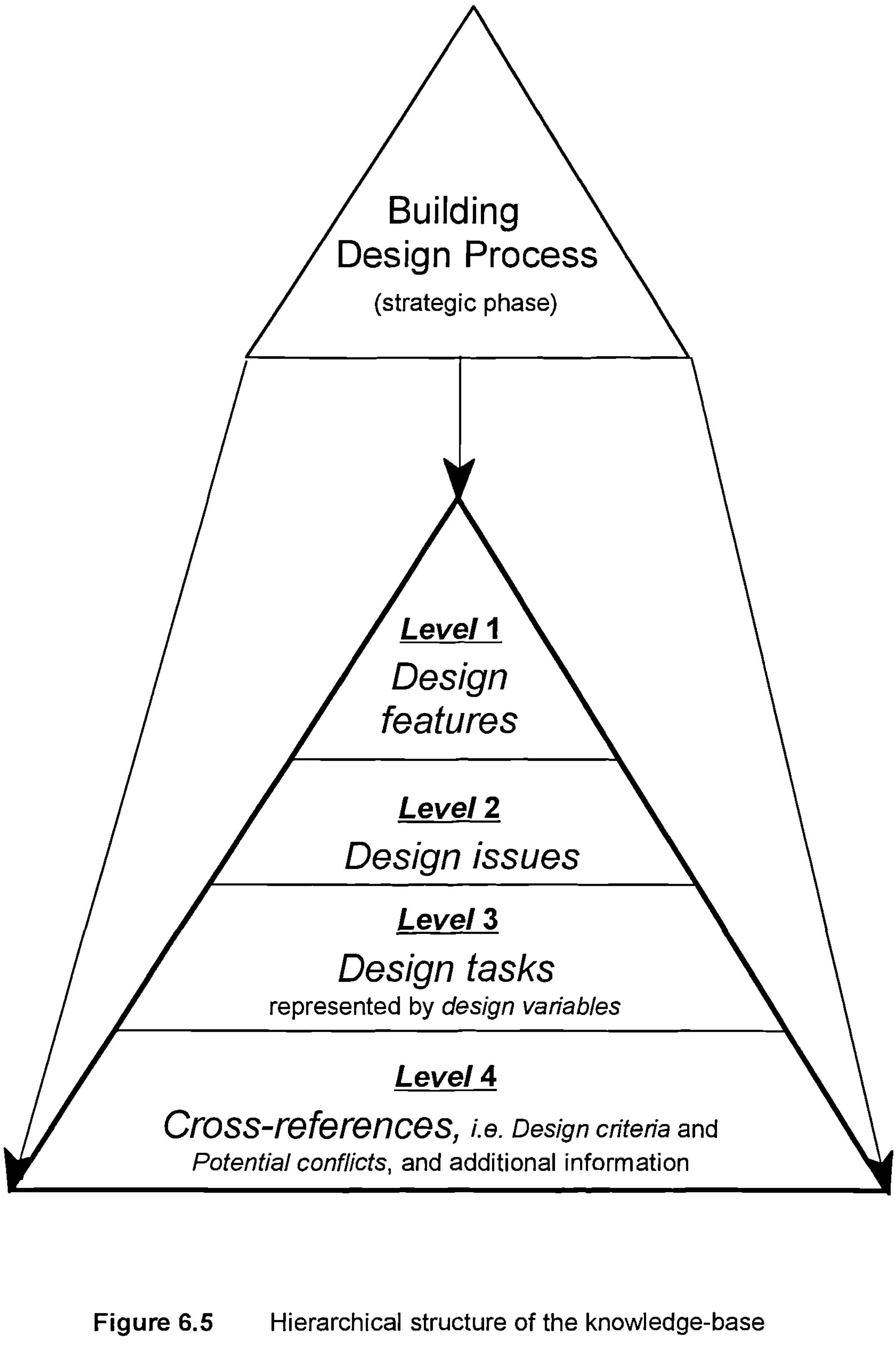


Figure 6.5 Hierarchical structure of the knowledge-base

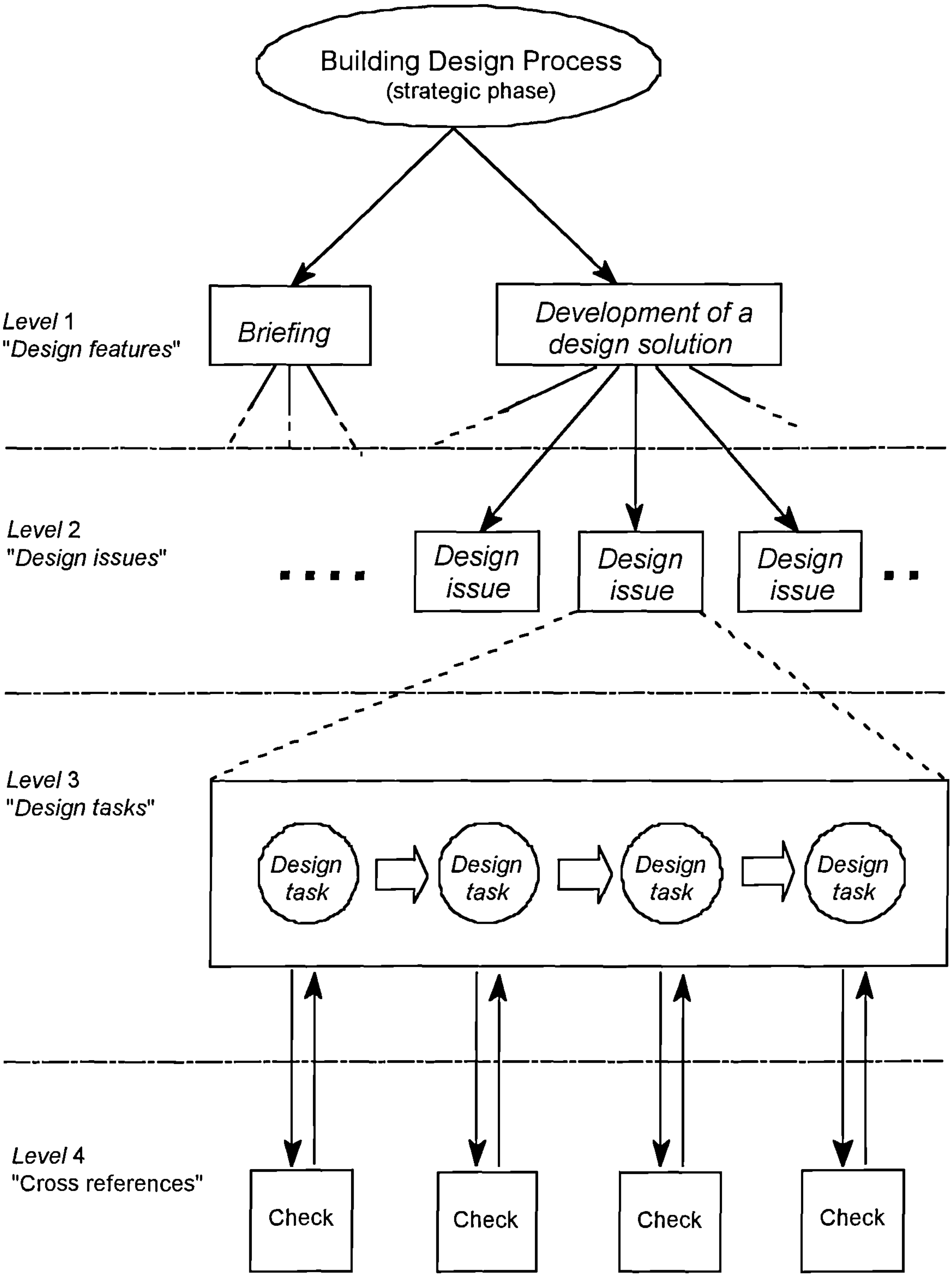


Figure 6.6 Outline of the prototype system operation

6.4.2 Modularization of the knowledge-base

Modularization is a key design concept for the efficient development as well as maintenance of the knowledge-base and its extendability. Here, a *knowledge-base module* may be considered as a set of rules with respect to a particular concept comprising the building design process. For example, a *knowledge-base module* may contain a set of rules which describe a sequence of *design tasks* associated with a particular *design issue*; another *knowledge-base module* may be responsible for process checking regarding a particular *design task.*

Such modularization was pursued using *Leonardo*'s *Multiple RuleSet* technique. The basic idea is that each of the concepts comprising the building design process, such as *design issues* and *design tasks*, is represented by an object; and the object frame of the object contains a *RuleSet* which deals with the objects associated with its subsidiary concepts (Figure 6.7). The rules contained within the object frame associated with *design issue "Window design"*, for example, describes the sequence of the *design tasks* originating from this *design issue* using the objects representing them; the object frames associated with these *design tasks* then contain the rules with regard to their cross-references. Such a *RuleSet* can be considered as a *knowledge-base module*. As this illustration suggests, the *RuleSets* may nest other *RuleSets* regarding their subsidiary concepts at one level down. An individual *RuleSet*, i.e. a *knowledge-base module*, can be developed only considering the subsidiary concepts associated with a particular concept at one level below in the conceptual hierarchy, and there is no need to consider other higher level concepts, or those of more than one level below.

The *knowledge-base modules* can, meanwhile, be associated with the conceptual hierarchy which was described in Section 6.4.1. As a result, the locations where these *knowledge-base modules* are allocated, are related to the conceptual hierarchy, as shown in Figure 6.8, namely:

(i) *Level* 1: *Main RuleSet*

The rules containing the object representing the *design features* (*design feature objects*) are described in *Main RuleSet*, together with the control directives.

(ii) *Level* 2: *Design feature object frames*

The *RuleSets* concerned with the *design issues* associated with a *design feature* are contained within a *RuleSet* slot of its associated *design feature object frame*.

(iii) *Level* 3: *Design issue object frames*

A *RuleSet* involving *design task objects* is expressed within the *RuleSet* slot of a *design issue object frame*.

(iv) *Level* 4: *Design task object frames*

Rules regarding process checking procedures are described within the *RuleSet* slot of a *design task object frame*. A complicated procedure may be modularized by representing it with an object, which may be called a "*reference object*", and encapsulating it within the associated object frame.

Leonardo's *Multiple RuleSet* technique eventually allows these *knowledge-base modules* to be integrated into an entire knowledge-base using "*Merge*" command (Figure 6.9). Modularizing the knowledge-base using the *Multiple RuleSet* technique may therefore help developing the knowledge-based system in association with the conceptual hierarchy.

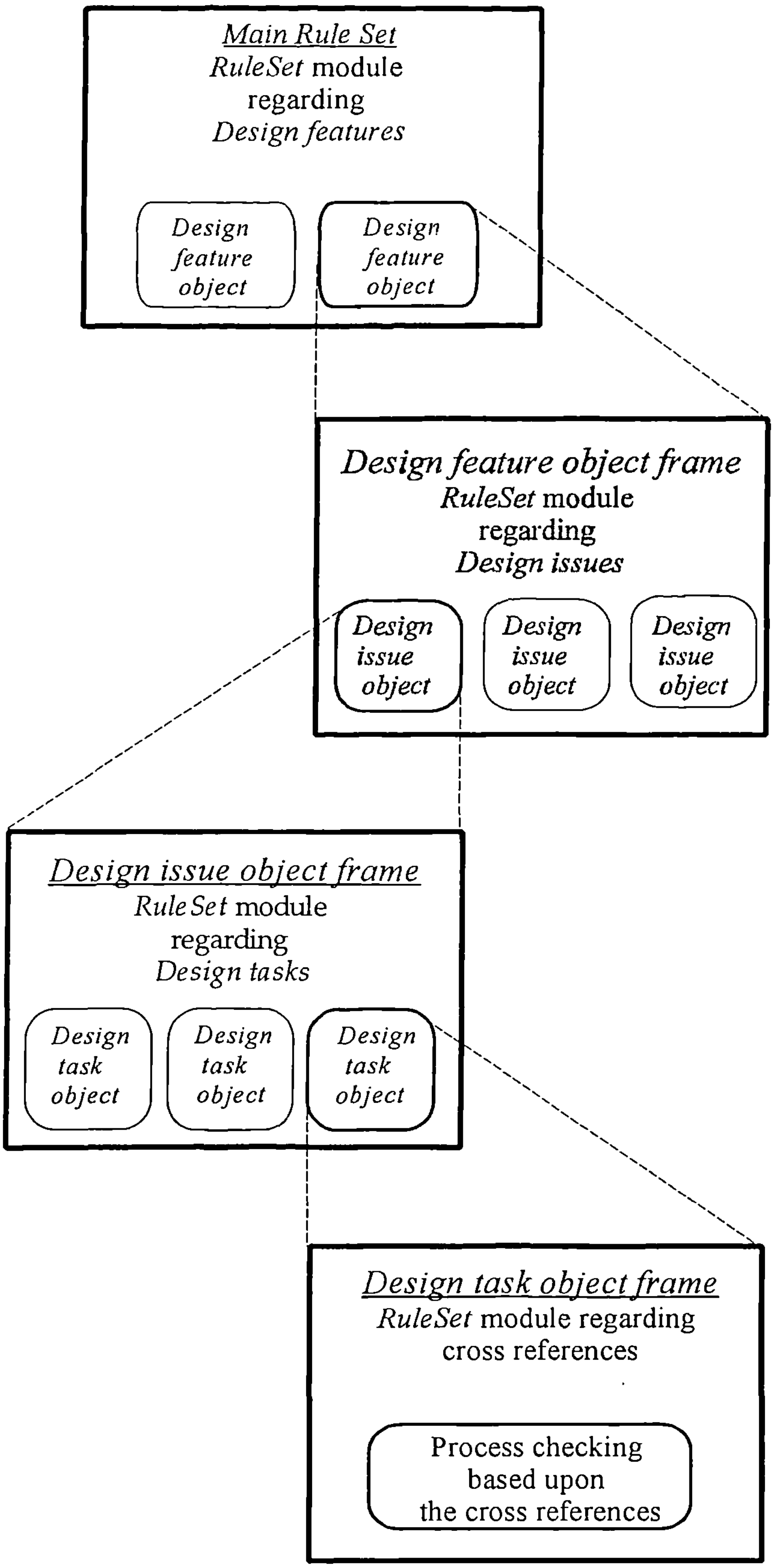
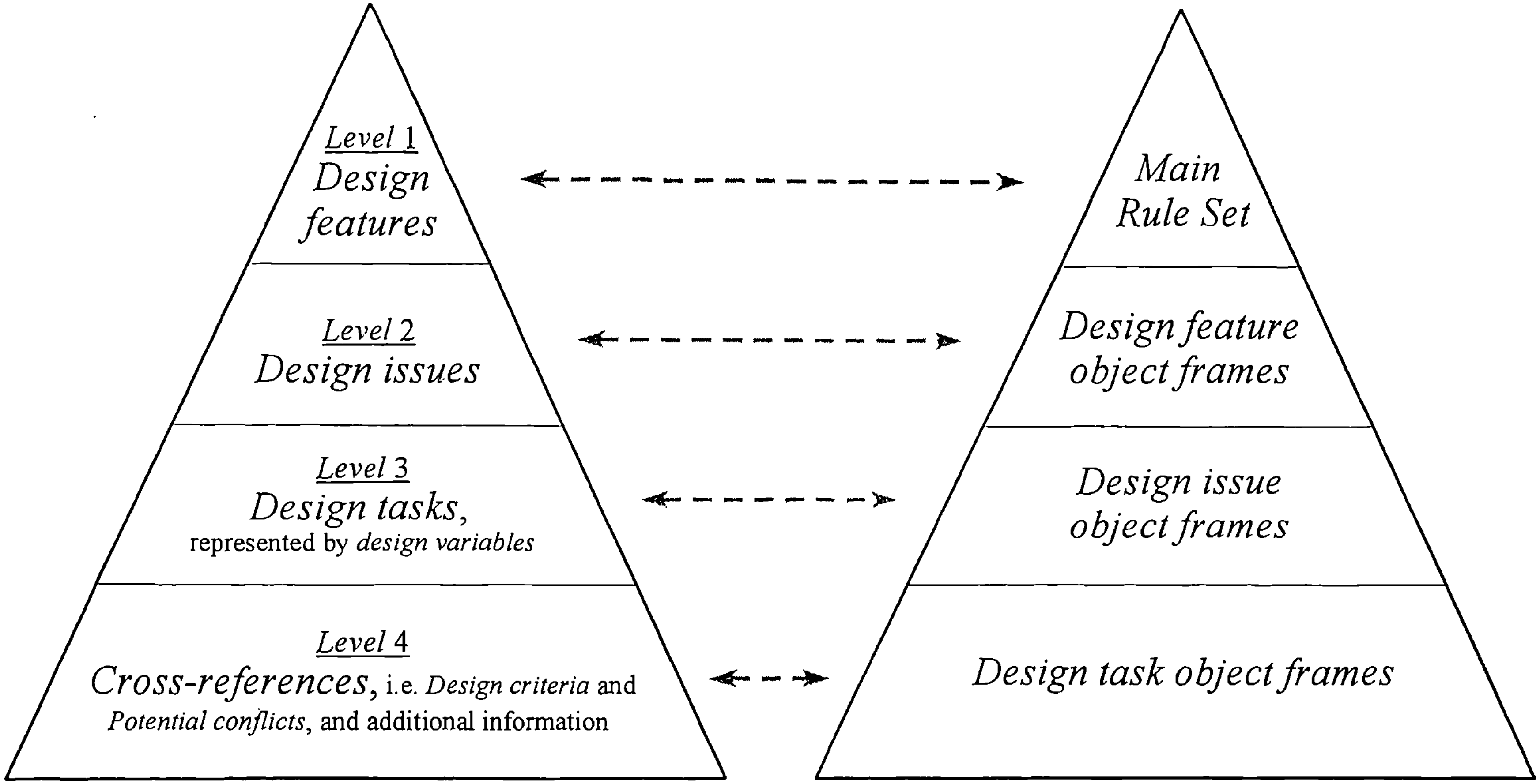


Figure 6.7 Nested *RuleSet* modules of the knowledge-base
A subsidiary *RuleSet* is contained within an object frame.



(a) Conceptual hierarchy

(b) Place where the *RuleSet* concerned with a particular concept is allocated.

Figure 6.8 Places where *RuleSets* regarding particular concepts are allocated, in relation to the conceptual hierarchy

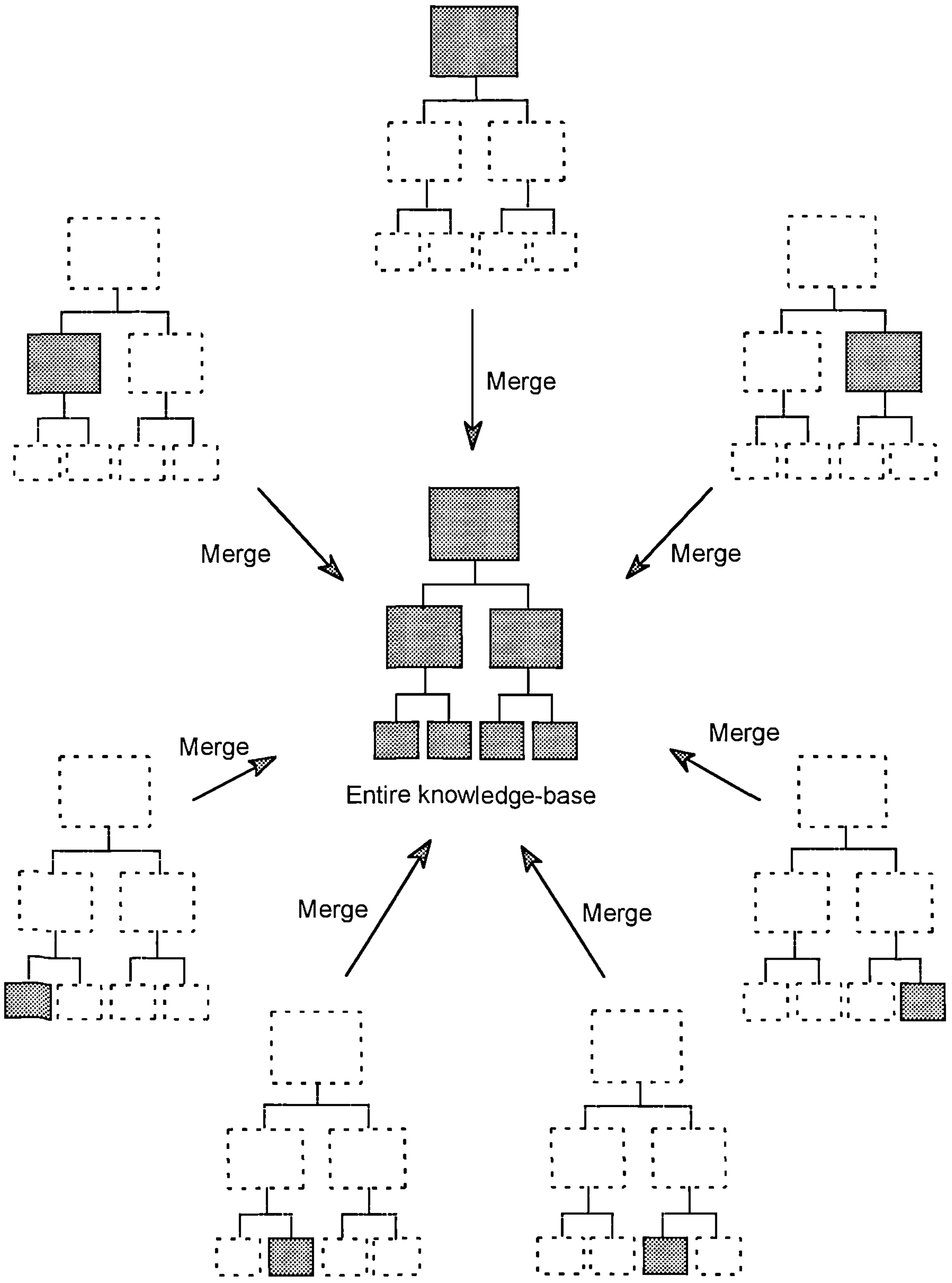


Figure 6.9 *Knowledge-base modules*, and integrating them into an entire knowledge-base using "*Merge*" command

6.5 The Operation of the Prototype System

As briefly explained in Section 6.4.1, the prototype system's operation begins with specifying a *design feature* and *design issue* of interest. When a particular *design issue* is selected, the system allows the user to undertake the *design tasks* originating from the selected *design issue* in a logical sequence. The prototype system's entire operation is illustrated in a flow chart shown in Figure 6.10, which is explained in detail below.

(1) Specifying a *design feature*

Since the design process was considered to consist of two different features, i.e. "*briefing*" and "*development of a design solution*", the prototype knowledge-based system asks the user which feature is required at the beginning of the session (Figure 6.11). It presents a screen in which the *design features* are shown together with the RIBA (Royal Institute of British Architects) *Plan of Work* stages (Figure 6.12). The user can obtain the explanation regarding each of the *design features* through *hypertext* screens. Pressing the function key <F3> provides a help screen which explains the key operations.

Once the *design feature* to proceed, either "*briefing*" or "*development of a design solution*", has been determined, the prototype system will present its associated *design issues*, so that the user can specify which *design issue* is to be carried out. Figure 6.14 outlines the further operations concerned with "*briefing*". (For "*development of a design solution*", they are outlined in Figure 6.17.) Since the operations are slightly different depending upon the *design features*, those associated with "*briefing*" will be described first, and then those related to "*development of a design solution*".

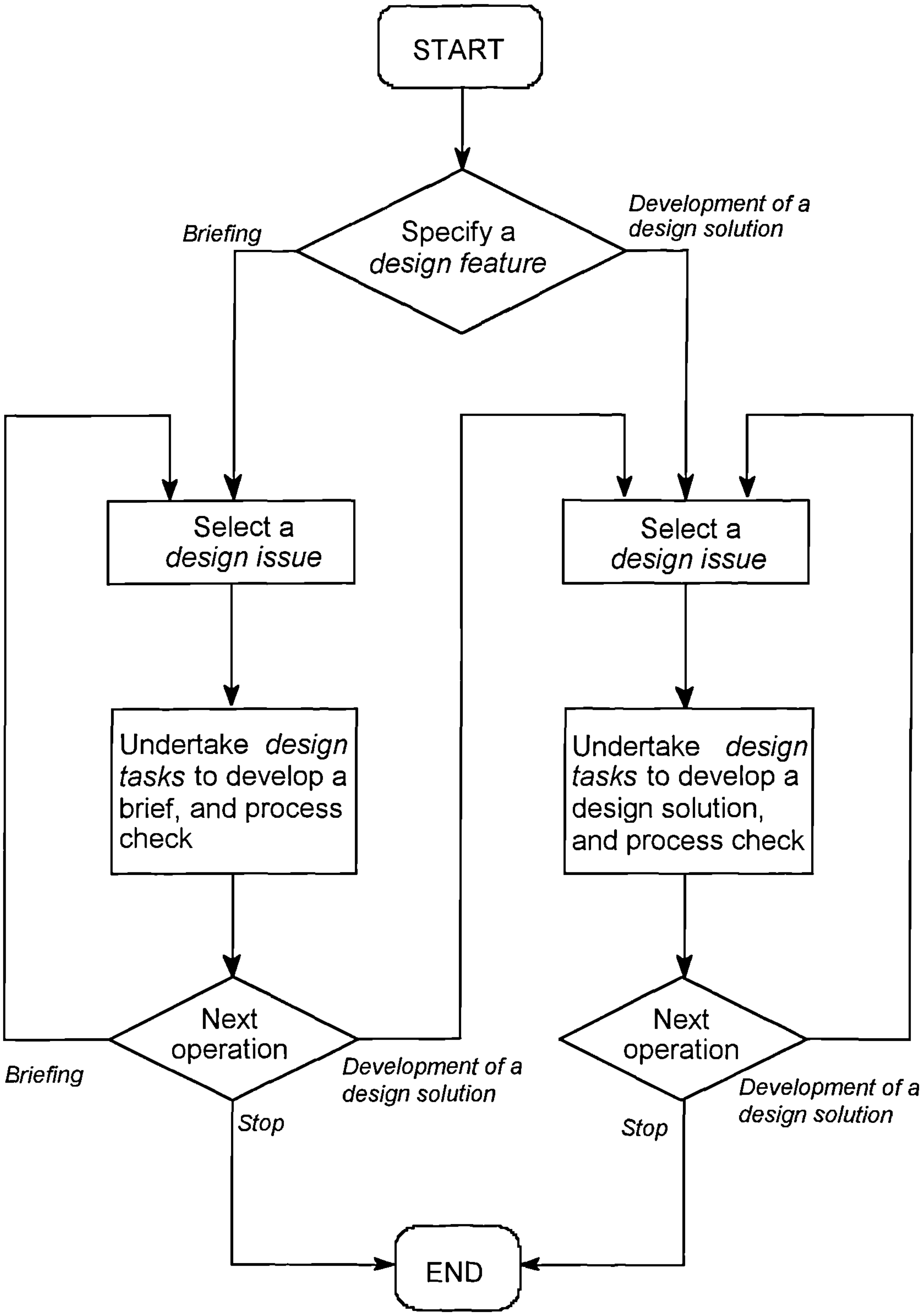


Figure 6.10 Flow chart showing the prototype system's operation

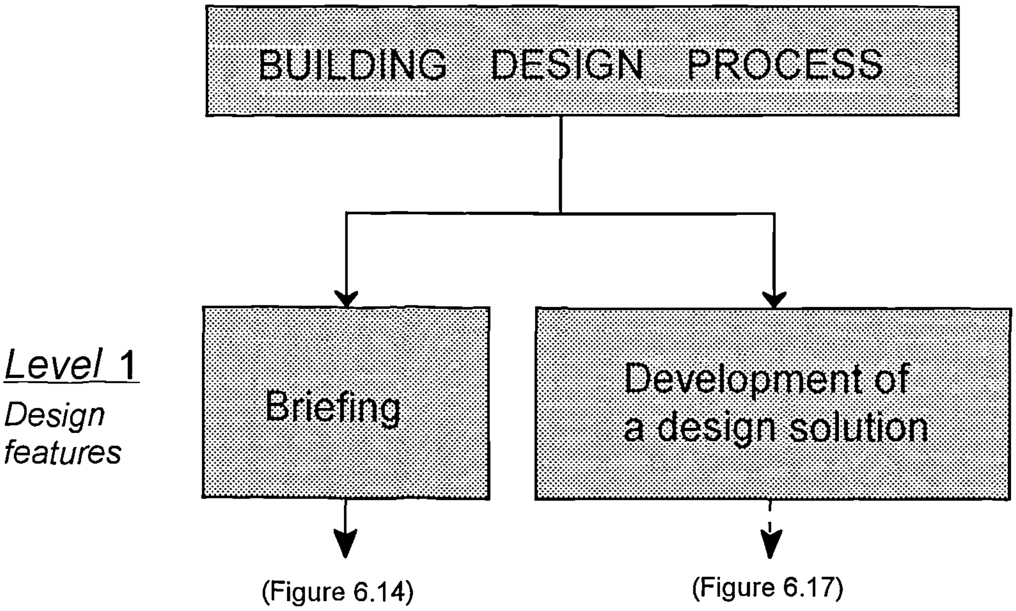


Figure 6.11 The prototype system's operation: Specifying a *design feature*, either "*Briefing*", or "*Development of a design solution*".

A. Operations associated with "briefing"

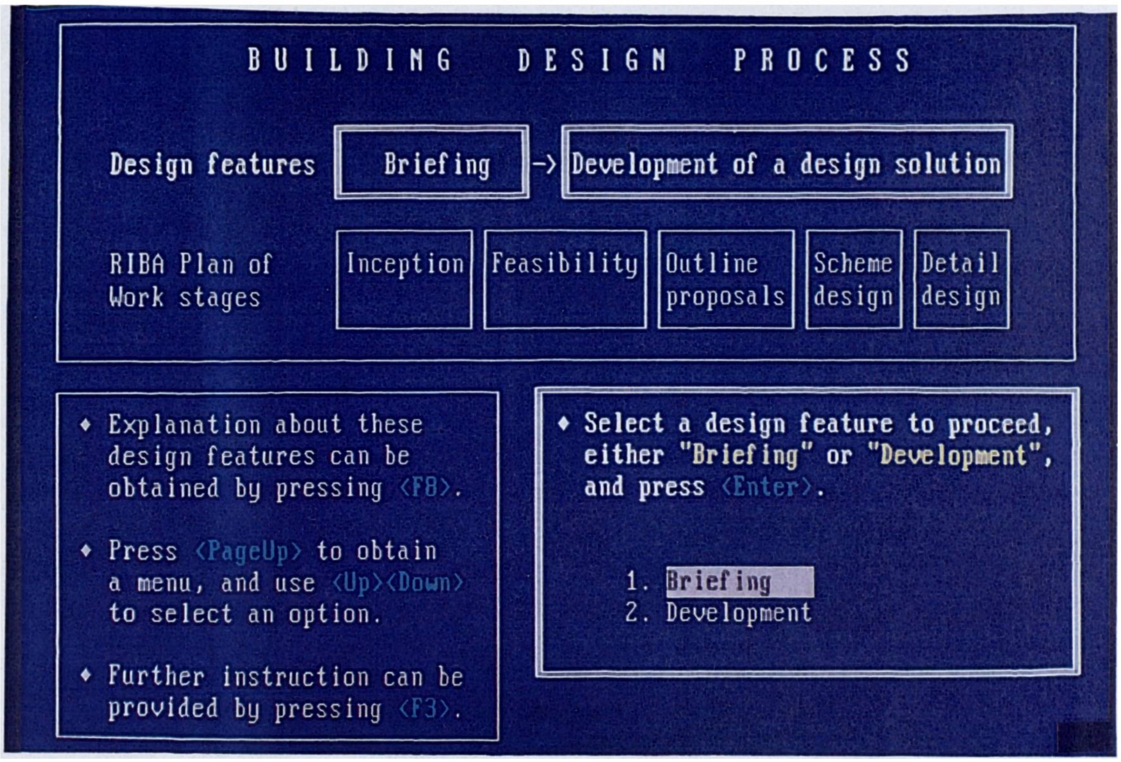
(2) Specifying a *design issue* to develop a brief

When the *design feature* "*briefing*" has been selected, the system presents a screen which indicates the *design issues* associated with the briefing phase, i.e. "*General outline of the requirements*", "*Design objectives*", "*Context of the scheme*" and "*Feasibility study and performance criteria*" (Figures 6.13 and 6.14). As illustrated in Figures 6.13 and 6.14, "*Feasibility study*" is treated as a part of "*Performance criteria*" where feasible environmental standards are established, even though they were separate *design issues* when the building design process was described rationally in Chapter 4. The user is allowed to specify one of these *design issues* while obtaining explanatory information about each of them through a *hypertext* screen.

(3) Undertaking *design tasks* to develop a brief

Unlike the previous two operations, the prototype system informs the user of the design tasks to consider, related to the *design issue* specified, so that fundamental activities during the *briefing* phase will not be missed. When either "*General outline of the requirements*" or "*Context of scheme*" has been selected, it will present a sequence of screens describing each of the *design tasks* originating from the *design issue*. These screens provide the explanation about the *design tasks* (obtaining the information regarding the client's requirements and examining the site conditions), as well as showing a list of design decisions which may be affected by the information later on in the design process. For the *design issue* "*Design objectives*", the prototype system presents the screen from which the user may obtain an explanatory screen about *Design aspects*, such as "*visual environment (lighting)*", as shown in Figure 6.15. If the option "*Feasibility study and performance criteria*" has been selected, meanwhile, the prototype system assists the user to establish feasible performance criteria by asking questions on the basis of the checklist developed in Chapter 4, as well as providing design information. Figure 6.16 shows an example of the provision of design information (standard service illuminance and representative activities/interiors). The *knowledge-base modules* to carry out process checking were developed to support "*illuminance level*", "*uniformity*", "*target average daylight factor*" and "*colour properties*".

When a specified *design issue* has been completed, the prototype system allows the user to decide the next action, i.e. either to (i) repeat "*briefing*" for another *design issue* related to this *design feature*; (ii) move onto the other *design feature*, i.e. "*development of a design solution*"; or (iii) quit the session (see Figure 6.10).



B U I L D I N G   D E S I G N   P R O C E S S

Design features   Briefing -> Development of a design solution

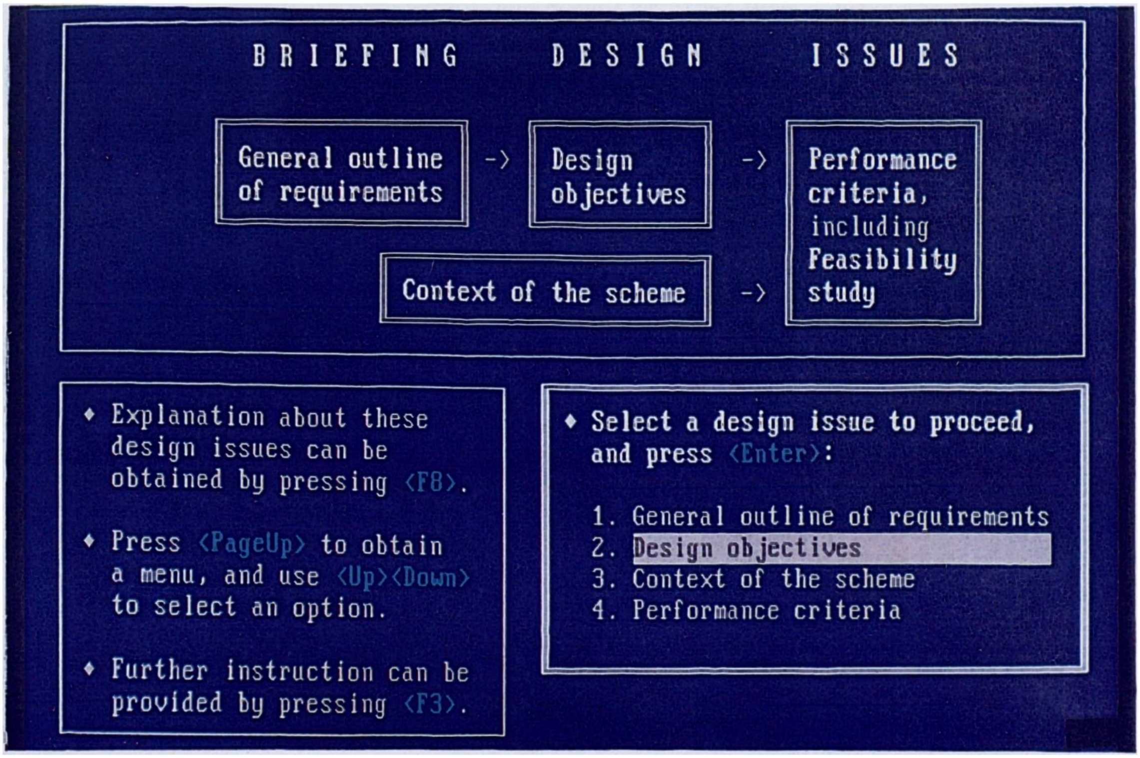
RIBA Plan of Work stages   Inception   Feasibility   Outline proposals   Scheme design   Detail design

- Explanation about these design features can be obtained by pressing <F8>.
- Press <PageUp> to obtain a menu, and use <Up><Down> to select an option.
- Further instruction can be provided by pressing <F3>.

- Select a design feature to proceed, either "Briefing" or "Development", and press <Enter>.

1. Briefing
2. Development

Figure 6.12 Screen for selecting a *design feature*



B R I E F I N G   D E S I G N   I S S U E S

General outline of requirements -> Design objectives -> Performance criteria, including Feasibility study

Context of the scheme ->

- Explanation about these design issues can be obtained by pressing <F8>.
- Press <PageUp> to obtain a menu, and use <Up><Down> to select an option.
- Further instruction can be provided by pressing <F3>.

- Select a design issue to proceed, and press <Enter>:

1. General outline of requirements
2. Design objectives
3. Context of the scheme
4. Performance criteria

Figure 6.13 Screen showing the *design issues* associated with "*briefing*"

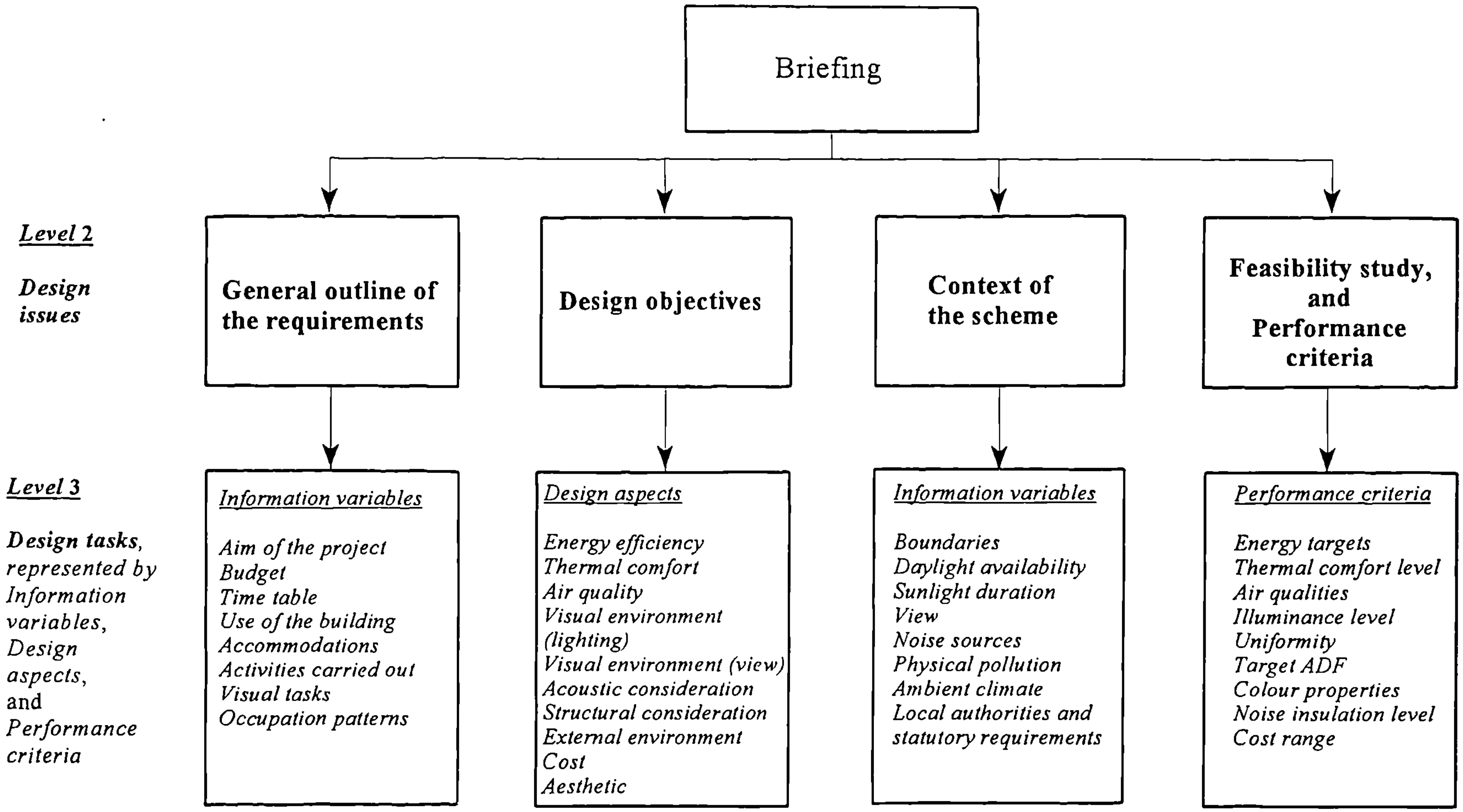
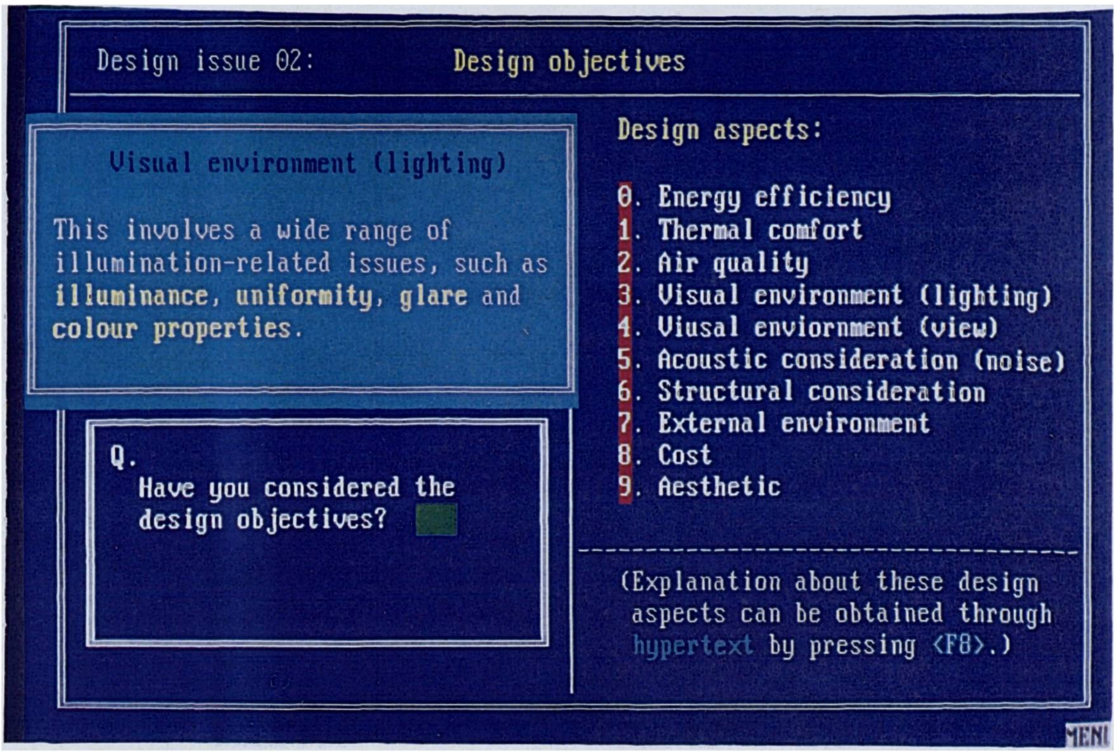


Figure 6.14 The prototype system's operation associated with the *design feature "Briefing"*:
Level 2 Design issues originating from *design feature "Briefing"*, and
Level 3 Design tasks, represented by *Information variables*, *Design aspects* and *Performance criteria.*



Design issue 02: Design objectives

Visual environment (lighting)

This involves a wide range of illumination-related issues, such as **illuminance, uniformity, glare** and **colour properties.**

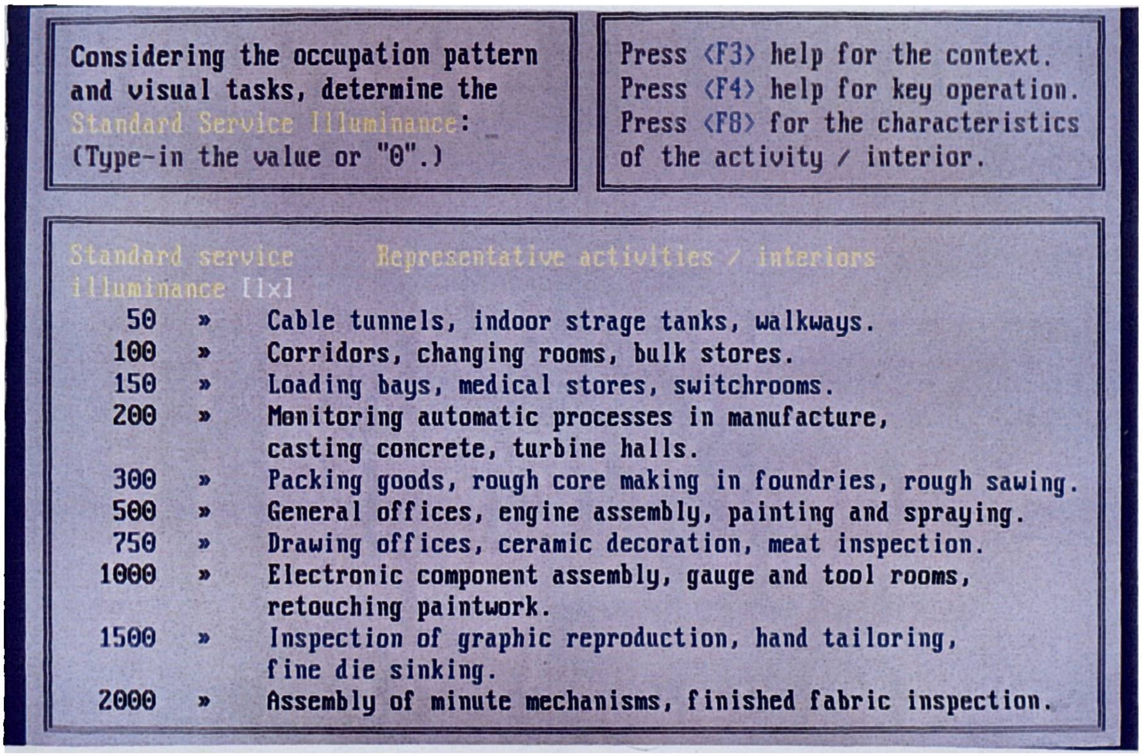
Q.
Have you considered the design objectives?

Design aspects:

0. Energy efficiency
1. Thermal comfort
2. Air quality
3. Visual environment (lighting)
4. Viusal enviornment (view)
5. Acoustic consideration (noise)
6. Structural consideration
7. External environment
8. Cost
9. Aesthetic

(Explanation about these design aspects can be obtained through hypertext by pressing <F8>.)

Figure 6.15 Screen for *design issue* "*Design objectives*", and a *hypertext* screen explaining a *design aspect* "*Visual environment (lighting)*"



Considering the occupation pattern and visual tasks, determine the Standard Service Illuminance: _
(Type-in the value or "0".)

Press <F3> help for the context.
Press <F4> help for key operation.
Press <F8> for the characteristics of the activity / interior.

Standard service illuminance [lx]		Representative activities / interiors
50	»	Cable tunnels, indoor strage tanks, walkways.
100	»	Corridors, changing rooms, bulk stores.
150	»	Loading bays, medical stores, switchrooms.
200	»	Monitoring automatic processes in manufacture, casting concrete, turbine halls.
300	»	Packing goods, rough core making in foundries, rough sawing.
500	»	General offices, engine assembly, painting and spraying.
750	»	Drawing offices, ceramic decoration, meat inspection.
1000	»	Electronic component assembly, gauge and tool rooms, retouching paintwork.
1500	»	Inspection of graphic reproduction, hand tailoring, fine die sinking.
2000	»	Assembly of minute mechanisms, finished fabric inspection.

Figure 6.16 Provision of design information: Standard service illuminance and representative activities/interiors

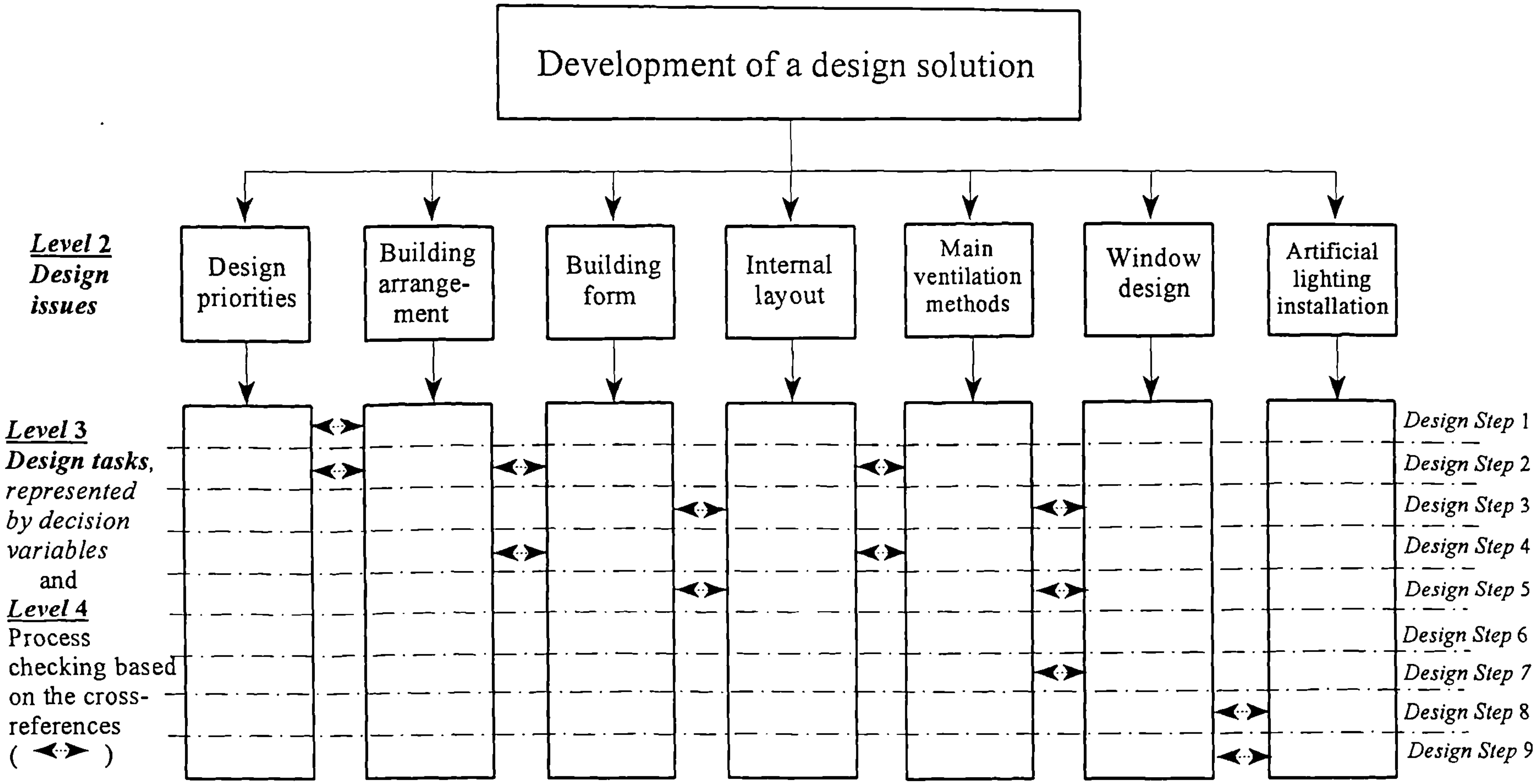
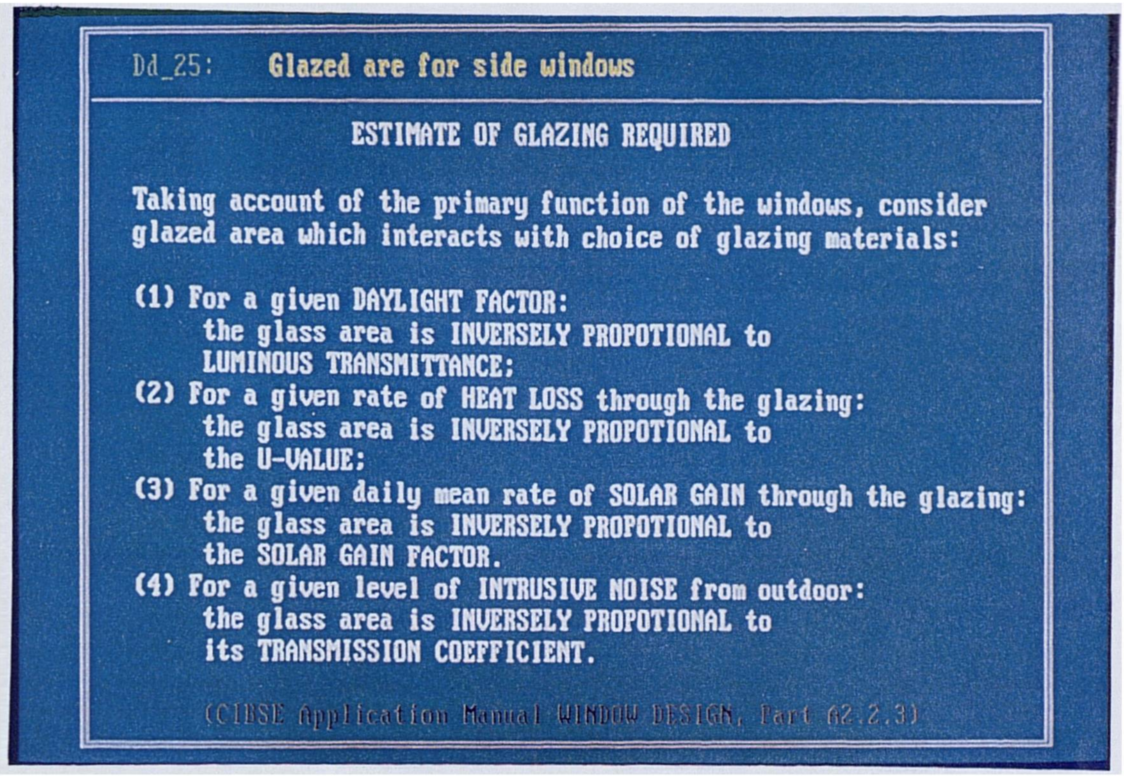
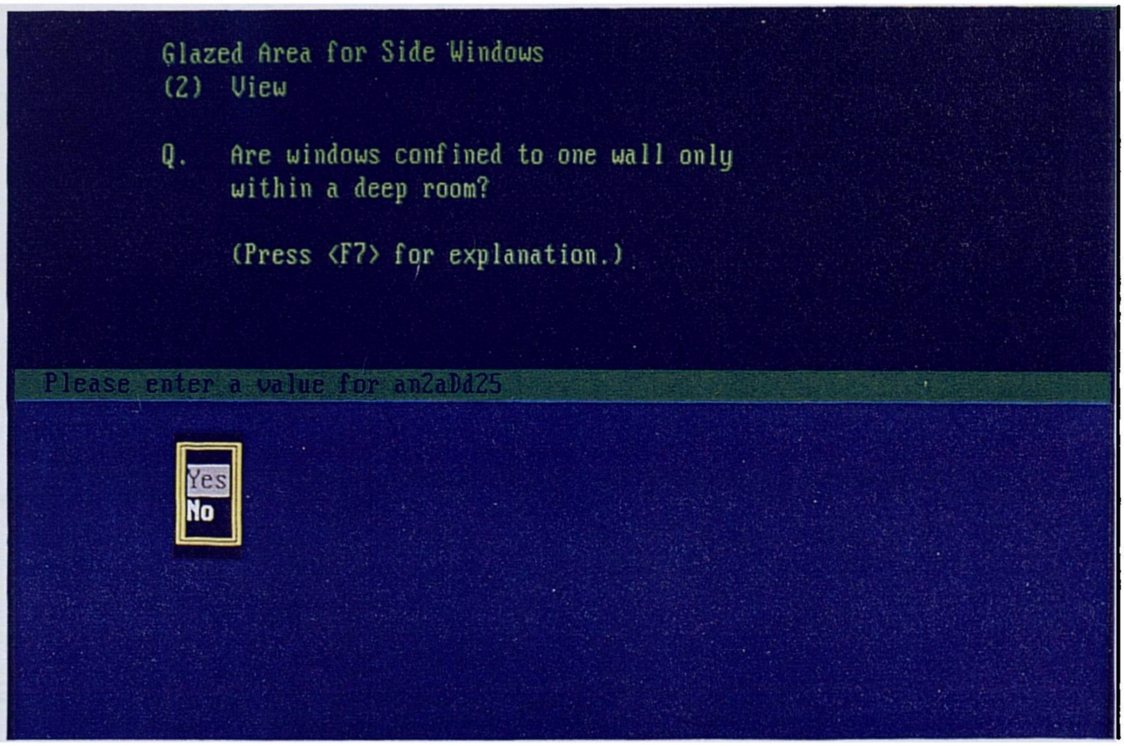


Figure 6.17 The prototype system's operation associated with the *design feature "Development of a design solution"*:
Level 2 *Design issues* originating from *design feature "Development of a design solution"*;
Level 3 *Design tasks*, represented by *Decision variables* in relation to *Design Steps*; and
Level 4 Cross references.



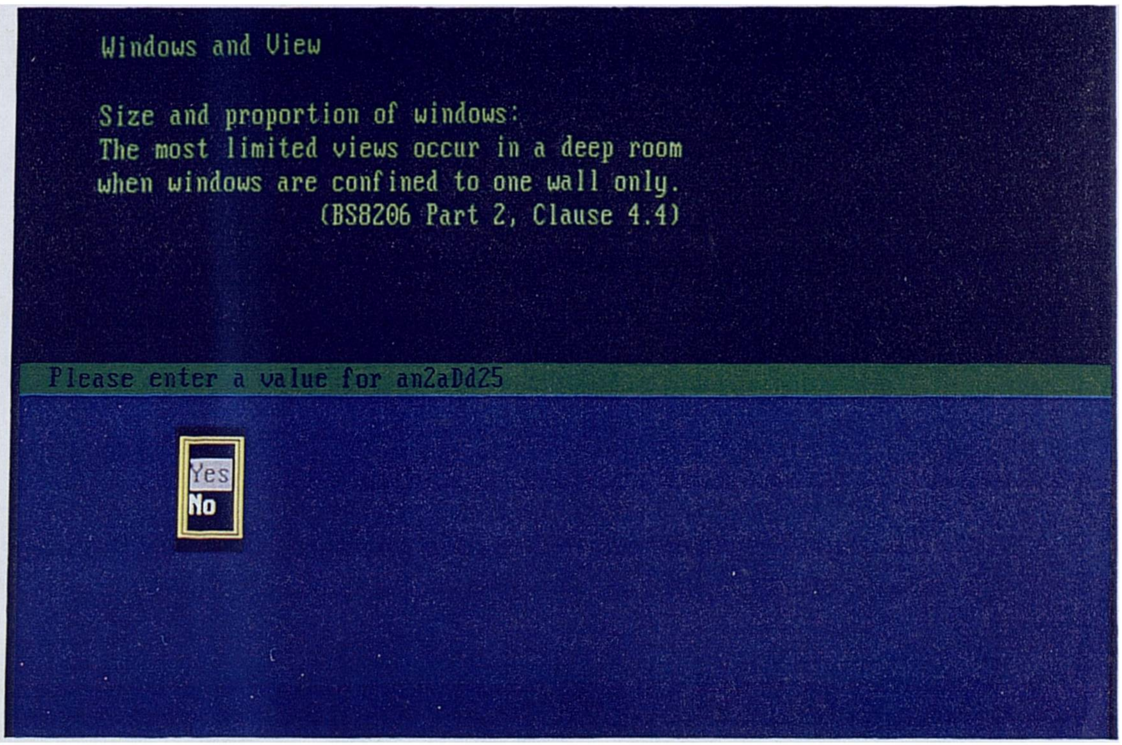
```
Dd_25:     Glazed are for side windows

                ESTIMATE OF GLAZING REQUIRED

Taking account of the primary function of the windows, consider
glazed area which interacts with choice of glazing materials:

(1) For a given DAYLIGHT FACTOR:
      the glass area is INVERSELY PROPOTIONAL to
      LUMINOUS TRANSMITTANCE;
(2) For a given rate of HEAT LOSS through the glazing:
      the glass area is INVERSELY PROPOTIONAL to
      the U-VALUE;
(3) For a given daily mean rate of SOLAR GAIN through the glazing:
      the glass area is INVERSELY PROPOTIONAL to
      the SOLAR GAIN FACTOR.
(4) For a given level of INTRUSIVE NOISE from outdoor:
      the glass area is INVERSELY PROPOTIONAL to
      its TRANSMISSION COEFFICIENT.

      (CIBSE Application Manual WINDOW DESIGN, Part A2.2.3)
```

Figure 6.18 An example of an outline of a *design task*



```
Glazed Area for Side Windows
(2)  View

Q.   Are windows confined to one wall only
     within a deep room?

     (Press <F7> for explanation.)

Please enter a value for an2aDd25
```

Figure 6.19 A query screen, using a *Leonardo* default screen

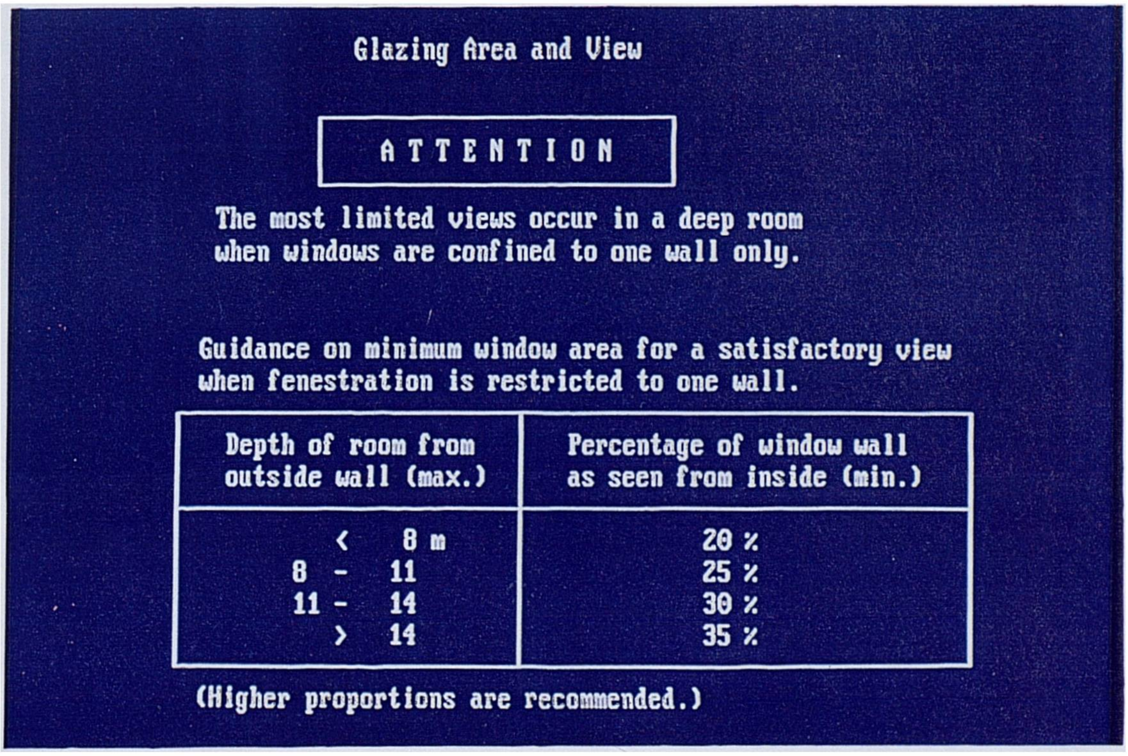


Windows and View

Size and proportion of windows:
The most limited views occur in a deep room
when windows are confined to one wall only.
(BS8206 Part 2, Clause 4.4)

Please enter a value for an2aDd25

Figure 6.20 Provision of explanation (after pressing <F7>)



Glazing Area and View

ATTENTION

The most limited views occur in a deep room
when windows are confined to one wall only.

Guidance on minimum window area for a satisfactory view
when fenestration is restricted to one wall.

Depth of room from outside wall (max.)	Percentage of window wall as seen from inside (min.)
< 8 m	20 %
8 - 11	25 %
11 - 14	30 %
> 14	35 %

(Higher proportions are recommended.)

Figure 6.21 An example of an "ATTENTION" screen shown during process checking

B. Operations associated with "development of a design solution"

The operations associated with the "*development of a design solution*" are illustrated in Figure 6.17.

(4) Specifying a *design issue* to develop a design solution

As illustrated in Figure 6.17, once the *design issue* "*development of a design solution*" has been selected, the system presents seven *design issues*, i.e. "*Design priorities*", "*Building arrangement on the site*", "*Building's form*", "*Internal layout*", "*Main ventilation methods*", "*Window design*" and "*Artificial lighting installation*", as a set of options from which *a design issue* of interest may be selected.

These *design issues* could have been split into individual *design tasks*, and re-organised in terms of the *Design Steps*, which were defined in relation to the logical sequence of the design activities (see Section 4.4). In which case, each of the *Design Steps* would have contained *design tasks* from different *design issues*, and, as a result, the user could have dealt with them within a *Design Step* as the process progressed. In a sense, such an arrangement of *design tasks* could have demonstrated inter-disciplinary design working. The prototype system was, however, designed to allow the selection of a particular *design issue* and execution of the *design tasks* originating from it, rather than forcing the user to deal with various *design tasks* across different *design issues*. This was because it was thought that

- considering the reality of the practice, every designer involved in the process should have a particular background and interest;
- in this sense, a *design issue* is considered to represent such a background and interest, and, therefore, may be regarded as a unit of design process;
- allowing the design process to be carried out in terms of the *design issues* would be more realistic;
- a computer-based design aid of this kind is likely to be used with a particular interest in terms of the *design issue*; and
- operating in this way may be more capable of conveying the understanding of inter-disciplinary design working, rather than re-organising the *design tasks*.

In this project, *knowledge-base modules* were developed for "*Design priorities*", "*Window design*" and "*Artificial lighting installation*".

(5) Undertaking *design tasks* to develop a design solution

Once a particular *design issue* has been specified, the prototype system will assist the user in carrying out the series of *design tasks* originating from the selected *design issue* in a logical sequence. At the beginning of each of the individual *design tasks*, a "summary" of the *design task* is presented. Figure 6.18 illustrates an example of such a screen.

The knowledge-base module associated with the *design issue* '*Design priorities*' involves a function which is designed to deal with stereotypes for an office building. The knowledge-base presents four examples of stereotypes, or forms, with regard to an office building as shown in Figure 4.7 in Section 4.3.1, so that the user may select one of the forms after considering the briefing and the design priorities. Similarly, the knowledge-base module for the design issue '*Window Design*' contains the examples of cells, or space forms, which are presented in Figure 4.8 in Section 4.3.1. The IKBS presents these cells, so that the designer can use them as a starting point for internal space when he/she considers daylighting design aspects.

As the process advances, the user is questioned on the basis of the checklist developed in Chapter 4, using *Leonardo*'s *Default Screens*, and process checking is undertaken during the course of the *design task*. Figure 6.19 shows an example of the questions associated with *design task* "*Glazed area for side windows*". Function key <F7> facilitates the user to obtain further information or an explanation regarding the question (Figure 6.20). Such a function can allow the user to obtain relevant information at pertinent stages. Depending upon the user's answer, the system may draw attention to or provide suggestions regarding the design decision (Figure 6.21).

The knowledge-base then checks the user's choice taking account of the decisions associated with other design tasks such as '*daylight priorities*'. Process checking may take place in three steps, as illustrated in Figure 6.22. These steps are:

(a) Process checking before potential design decision making

The process checking in this step is concerned with "outside information", such as the client's requirements and site conditions, and "timing of decision-making". A series of questions prompt the user to consider relevant outside information which might affect the design decision. Referring to the logical sequence of the *design tasks*, on the other hand, the system ensures that the *design decisions* which may affect the current *design task* have been made. An alert will be raised if any of these *design tasks* have not yet been considered. This step can be regarded as the "*information*" and "*analysis*" phase of the three-space model.

(b) Potential design decision

The user may derive an initial proposals from a stereotype, and then develop a potential design solution by making a decision. The system may offer options for a particular design decision using a menu, taking account of the conditions examined during the previous step. It may also provide necessary design information to make a decision. This step can be considered as the "*modification*" of the three-space model.

(c) Process checking after the potential design decision making

When a potential design decision has been made, the prototype system may ask the user a series of questions to draw attention to the performance characteristics, i.e. the *design criteria*, to be evaluated. The system also examines the decision in terms of its *potential conflicts*. An alert will be raised if any likelihood of conflict against the preceding design decisions is detected, so that any omission or error can be avoided. This step may be regarded as the "*evaluation*" of the three-space model.

External simulation software packages may be brought in, and used for the evaluation of the potential design decision (see Figure 6.22). These simulation programs could then become a part of the process checking function with regard to a particular design criterion. In other words, the rather discipline-specific but sophisticated software packages could be integrated with the IKBS's process handling functions, so that the power of such back-end processors could be effectively utilised within the context of the building design process. When an ultimate integrated building design environment is developed, external evaluation capabilities should be integrated with the IKBS's process handling functions at this process checking step, taking account of design data exchange between them. The prototype system has not been integrated with any particular external simulation programs in terms of the building data model, but it was designed to demonstrate such a system framework to provide the connection with external simulation software such as "*Daylighting program*", a daylighting simulation program, within the context of the design process.

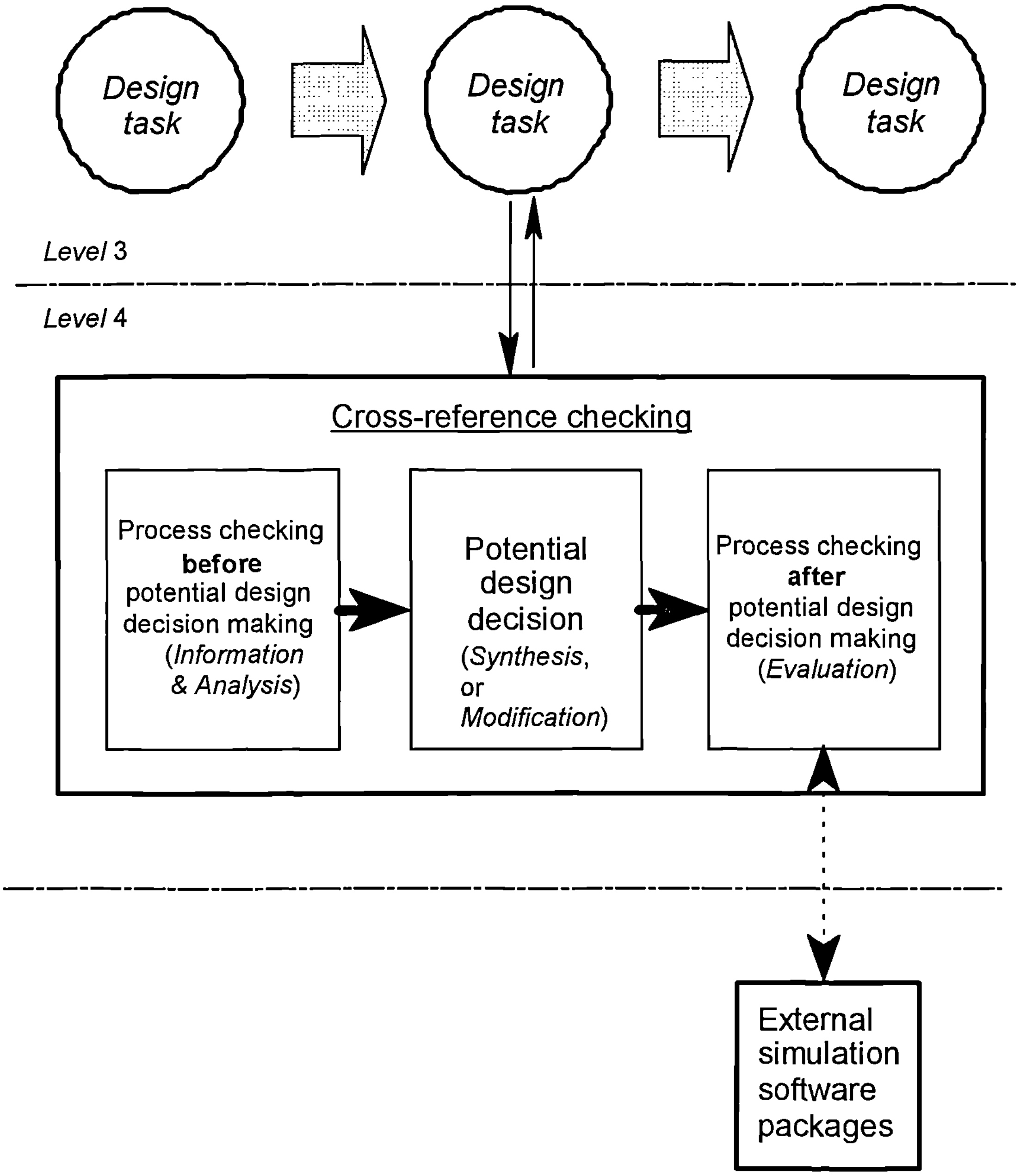


Figure 6.22 Three steps of process checking at *Level* 4, and external evaluation tools (simulation software packages).

6.6 Assessment of the Prototype System

The performance of the prototype system was assessed in terms of the functions of an IKBS for inter-disciplinary design working described in Section 5.3.3 of this thesis.

(1) Demonstrating inter-disciplinary building design working

The framework developed to aid inter-disciplinary building design working was implemented within the prototype system by developing the knowledge-base in relation to the conceptual hierarchy of the building design process. Although the *knowledge-base modules* for the *design tasks* were developed for "*Design priorities*", "*Window design*" and "*Artificial lighting installation*" as well as those originating from the "Briefing", this implementation enabled the prototype system to demonstrate the use of such a design aid with particular reference to daylighting and lighting design aspects. Operating on the basis of the framework, the prototype system can allow the user to undertake a logical sequence of the *design tasks* associated with a particular *design issue* from multi-disciplinary points of view.

The prototype system also takes account of the provision of stereotypes. The knowledge-base module for "*Design priorities*" was designed to present examples of stereotypes for an office building form. The system's capability of dealing with stereotypes is still relatively primitive, because (a) *Leonardo*'s graphic capability is limited; (b) the production system, the IKBS technique used in this project, does not handle such 'loose' knowledge well; and (c) the stereotypes themselves need to be studied in terms of knowledge acquisition and representation.

(2) Providing the guidance for inter-disciplinary building design working

The objectives of this work involve that it was to examine the feasibility of utilising on IKBS as a core module in an integrated computer-based design environment, and that its function should be to provide guidance, information and checking function.

The provision of guidance for inter-disciplinary building design working was achieved, although limited to daylighting and lighting design aspects, by supplying explanations about the design process both when specifying a particular *design feature* or *design issue* and during a question and answer session when a sequence of *design tasks* is being undertaken. Because of the multi-disciplinary features of the building design process, the *hypertext* facilities were found to be a powerful means of providing such inter-related concepts. The user interface of the prototype system was developed so that most of the guidance was provided through *Leonardo*'s default screens, which have a limited ability to present information. Further improvement of the user interface should enhance the IKBS's capability of providing appropriate guidance and other information in an accessible form. Since Leonardo does not provide any drawing capability other than very simple graphic functions, its graphic function to present stereotypes needs to be improved by external programs. For further development of the IKBS taking account of stereotypes in particular, a sophisticated graphic interface needs to be developed, as well as further study on stereotypes themselves. This would be carried out in the context of an integrated design environment.

(3) Checking the design process

The prototype system's process checking capability was achieved in two ways. The "building design process" was checked via a series of questions which drew attention to vital design aspects on the basis of the checklist, so that an appropriate design procedure could be followed. It could also assess a "design decision" from a multi-disciplinary point of view, based upon the cross-references. Both types of process checking functions included presenting an alert or suggestion to the user.

(4) Providing extensive design data

Design data from written sources, such as the CIBSE *Code for Interior Lighting*, stored in its knowledge-base, enabled the prototype system to provide information at pertinent stages of the design process. In this sense, the prototype system can act as an information system for building design with particular reference to daylighting and lighting design. Such a capability may be extended by being integrated with an external data-base. The prototype system proved its potential as an information resource which aids extensive use of design information.

(5) Automatic decision-making

In order not to take the control of the design process from the user, the prototype system's automatic decision-making capability was limited to deciding target illuminance in relation to the activities carried out, which is considered to be a low-level decision-making procedure. In this case, the system presents its decision so that the user has an opportunity to confirm it. The prototype system could prepare appropriate options regarding rooflight profiles and lighting control strategies, but it was designed to leave the final decision-making with the user.

Chapter 7

Chapter 7

CONCLUSION AND DISCUSSION

7.1 Conclusion

It was argued that inter-disciplinary design working, as well as the effective and extensive use of design information, were vital to improving productivity in the building design process and to designing a quality-assured building. Within the inter-disciplinary working environment, every profession involved in a design project would be represented and would take part in the design process from the briefing stage, and design activities would be undertaken from various aspects associated with a final product using appropriate information. To enhance such a working environment, this project involved two major subjects, i.e. the development of a framework for inter-disciplinary design working, and the application of an intelligent knowledge-based system (IKBS) technique.

(1) Development of a framework for inter-disciplinary design working

It was considered that designers may derive an initial design proposal from a stereotype, and that they develop it taking account of its evaluation results. One of the challenges of this project was to establish a rationale which would allow both the linear time-related and parallel inter-disciplinary aspects of the building design process to be characterised.

A framework for inter-disciplinary design working was established describing the design process in terms of three kinds of *design variables*. The framework provided a basis for the checklist approach and, eventually, an IKBS for inter-disciplinary building design working. The ill-defined, open-ended problem was handled rationally in terms of the relationships between these *design variables*, while examining the domain knowledge, with particular reference to daylighting and lighting design aspects. During the course of the examination, systems engineering methods for studying the relationships between the *design variables* were found to be applicable to analyse the complicated features of the design process. Consequently, a logical sequence of the design activities was established which represents the linear time-related aspects of the building design process and its parallel inter-disciplinary features. In this sense, the framework may be process-oriented rather than solution-oriented. These were described in terms of the design criteria and potential conflicts. A checklist was eventually developed with particular reference to daylighting and lighting design aspects. The checklist has a process-checking capability, as well as exemplifying an inter-disciplinary daylighting and lighting design approach, by presenting the "watch points" for inter-disciplinary design working. Furthermore, since the related knowledge was examined based upon the relationships between the *design variables*, the framework also yielded the basis of knowledge management of the IKBS as well as its knowledge-base structure.

(2) Application of an IKBS technique

In order to demonstrate the framework for interdisciplinary design working, a prototype knowledge-based system was developed associated with the checklist, using a commercially available expert system shell, *Leonardo 3*. The knowledge-base of the system consists of the knowledge-base modules structured in association with the framework.

The prototype system allows the user to work through the logical sequence of the design activities with particular reference to daylighting and lighting design aspects, providing knowledge about the design process. In this sense, the prototype system has proved the viability of the checklist approach. Since it can provide pertinent information at a relevant stage, the prototype system also showed its potential as an information resource. This function should promote the effective use of design knowledge, and, as a result, may improve the productivity of the design process. The framework for inter-disciplinary design working was valuable as a basis for organising the information. In addition, it has a process checking capability which allows the user's design decisions to be assessed as the process progresses. With such a function, which was undertaken through a series of questions, the system will draw the user's attention to decisions known from its knowledge to be contradictory, and can, eventually, enhance the quality of the resulting design.

The knowledge was described in terms of the relationships between design variables. The knowledge-base consisted of knowledge-base modules each of which is associated with a *design task*. The system can, therefore, be extended further by modifying these individual modules and/or developing a new module, without changing the structure of the entire system. Such an extendibility will allow further development of the knowledge-based system.

The prototype system is not a design tool, however, but rather a design aid, or an information system, which has hardly any design capability unlike CAD tools. It is designed to demonstrate the framework, and acts as a process checker with particular reference to daylighting and lighting design aspects. It is believed that a drawing capability can be prepared independently, and that integrating the design aid with such a design tool can provide a sophisticated and powerful computer-based design environment.

7.2 Discussion

(1) Promotion of inter-disciplinary design working

One of the main interests of this project was developing a basis for inter-disciplinary design working, in terms of a framework as well as a computer-based design aid. The importance of inter-disciplinary design working should be recognised further by those actually engaged in design work. In other words, in order to promote inter-disciplinary building design working a computer-based design aid alone is not sufficient, as Cooper and Crisp suggest [Cooper and Crisp, 1984]. Many designers tend to rely on customs and traditions which hinder, rather than enhance, inter-disciplinary design working. They may be unwilling to move in this new direction if it remains unfamiliar to them or is excessively difficult to implement. Unless those who practice are concerned with this subject, these kinds of products will have little chance of contributing to the promotion of inter-disciplinary working. In this sense, education and training will play a vital role in promoting inter-disciplinary design working.

(2) The application of the framework of design activities

The difficulties in rationalising the building design process can primarily originate from its complexity. But also they seem to arise from the difference between the design approaches of the disciplines, i.e. the use of stereotypes, or 'forms' as a starting point, is common in architectural design, whereas abstract principles seems to be important for engineering design, as described in Section 3.1. It was considered that designers may derive an initial design proposal from a stereotype, which is a loose form of a design solution, and that they develop it taking account of its evaluation results.

The rational description of the building design process provided a platform where the ill-defined and open-ended activities could be dealt with more systematically. The framework describes both the liner time-related and parallel inter-disciplinary aspects of the design process, by representing it in terms of the design steps, as well as the relationships between *design variables*. In this sense, the framework may be considered to be process-oriented rather than solution-oriented.

When the model was applied to the building design process, however, a great deal of work was required to define the *design variables* and to examine the relationships between them and the knowledge of the experts concerned. It is thought that not only is this due to the complicated features of inter-disciplinary working, but also because the application involves the interpretation of knowledge acquired. This suggests that the selection of design variables as well as the identified relationships between them may not only be associated with the physics involved in the building design process, but also related to the developer's perception, or understanding, of the design practice. In other words, the solution may not be one, but many depending on the experts involved. This specifically may relate to the use of stereotypes, and can be considered as a solution-oriented approach to the design problem. Ideally, any frameworks should allow flexibility of working methods. Further study seems necessary in order to combine the process-oriented approach of the framework and a solution-oriented approach to the building design.

(3) Knowledge acquisition

It was discovered that knowledge acquisition was a bottle-neck for successful IKBS development. Here, knowledge acquisition may imply two factors: 'amount' and 'quality' of knowledge. The 'amount of knowledge' relates to the comprehensiveness of the knowledge-base. In other words, whether or not an IKBS contains enough knowledge to cover the entire scope of the application. In this sense, the domain of the application has to be carefully defined particularly when an IKBS is considered for an ill-defined, open-ended problem. This aspect also requires consideration of the knowledge source for the application. As far as inter-disciplinary design working is concerned, the knowledge could ultimately be elicited from a design team which practises good inter-disciplinary working. In this case, knowledge elicitation techniques need to be selected carefully so that the multiple sources of knowledge, i.e. more than one expert, are appropriately dealt with. The organisation which provides education and training for inter-disciplinary building design working can be another source of expertise. (Some papers regarding the knowledge elicitation techniques can be found in the bibliography of this thesis.)

Meanwhile, the 'quality of knowledge' can be understood as 'usefulness of the knowledge' and its accuracy or dependability. When an IKBS is developed, knowledge needs to be represented in a form that a computer system can cope with. Since human experts (knowledge providers) may not always recognise the knowledge they use to solve a particular problem, developing an IKBS often requires a knowledge engineer, who is in charge of describing the expertise in a fairly rigid logic, to identify the implications within it. Whether the knowledge can be represented in a particular knowledge representation format is crucial. This may depend not only upon the knowledge engineer's capability, but also on the quality of the knowledge on which the knowledge engineer works. During the course of the development of the prototype system, it was found to be extremely complicated to produce sets of 'IF-THEN' rules from the itemised knowledge units, despite the fact that the knowledge was elicited from publications. Inter-disciplinary design working knowledge elicited from a design team may be even more difficult to transform into a set of rules.

To ensure the adequacy of an IKBS for inter-disciplinary design working, there are two points to consider. Firstly the knowledge elicitation process should be conducted carefully so that expertise can be obtained from designers in a suitable form associated with the knowledge representation technique used, such as "IF-THEN" rules. (Knowledge representation will be discussed more in relation to the application of the IKBS techniques below.) Secondly, it is preferable that the knowledge engineer who produces the sets of rules should also be aware of the needs of inter-disciplinary design working.

The knowledge-bases of a design aid for inter-disciplinary building design working can comprise not only knowledge about the relationships between the *design variables*, but also a ‘stereotype’, which is a generally held notion about the nature of a good solution to any recurrent building design problem [Hawkes, 1974]. It can be considered that such a stereotype forms a part of expertise of a designer. Usually knowledge is elicited, directly or indirectly, from an expert. In order to acquire a stereotype, however, it is also required to study a number of actual buildings which embody successful solutions.

This is because a stereotype is developed through practices over a period of time. It is, therefore, believed that such a design study is essential to draw a standard design idea, i.e. stereotype.

Here, the ‘stereotype’ ought to be loose enough not to intimidate the designer, but to give him a starting point and permit further development and exploration in the design process. Further study is needed to develop an appropriate manner to deal with such a relaxed and flexible notion in terms of both its acquisition and representation, so that the looseness of a stereotype is preserved.

(4) Application of the IKBS technique

The application of the IKBS techniques can be discussed in relation to two features of design activities, i.e. 'open-ended' and 'creative' work.

Most prominent IKBS applications such as medical or mechanical diagnoses and control problems, can be ill-defined problems, but few of them are open-ended. The majority of these problems are considered to have 'principles' which may be used to derive solutions. It is, however, hard, if not impossible, to express these principles explicitly in a direct method, e.g. a series of differential equations, due to particular features of the problems. An IKBS may be seen as an alternative approach to deal with such problems using the knowledge which describes the implication associated with a particular problem and then uses the system's inferencing capability. This suggests that one of the functions of the IKBS is to contain the intangible principle of the problem in a set of knowledge, and make it available through the reasoning process. Those applications were successful, possibly because well-defined "principles" exist behind those problems.

On the other hand, the 'principle' which an IKBS for inter-disciplinary building design working accommodates is different: it can manifest itself as a design working practice, while including the physics involved in a building, such as heat transfer. The working practice is not definite but can change depending upon technological development, the trends or fashions of the period, and the designers' philosophy. In this sense, one of the advantages of developing an IKBS for such an open-ended problem is considered to be its ability to act as a repository of knowledge so that the expertise can be utilised widely. This suggests that the reasoning capability of the IKBS may be of less importance, and that it is more important to select pertinent knowledge associated with a particular situation during the course of the building design process. In this sense, it is doubtful whether the use of production rules (IF-THEN rules) is appropriate.

It was, meanwhile, considered that the designers may possess stereotypes as a part of their expertise, as well as knowledge about causal relationships between design decisions and performance characteristics. The prototype system was designed to present examples of stereotype for a building form, although its graphic capability was limited. Through this project, however, it was felt that the production system may not be the best option to handle knowledge such as a stereotype. This is because:

(a) knowledge such as stereotypes cannot be described in 'cause-result' or 'condition-action' forms, i.e. through 'if-then' rules;

(b) the inference in design is far more complicated than that required in diagnosis, and therefore 'it-then' rules may be too simplistic to represent design knowledge.

Considering the 'formal approach' of architectural design, it is clear that the application of an IKBS has to overcome the knowledge acquisition and knowledge representation. Since a stereotype has to be loose [Hawkes, 1974], means of dealing with its looseness, or fuzziness, needs to be established in terms of both its representation and the inference mechanism. It is felt worthwhile to suggest examining other knowledge representation methods such as Minsky's frame theory(*) in the future. Perhaps, use of an object-oriented programming method might be an alternative approach to handle stereotypes. It also seems worth mentioning about case-based KB approach as an alternative for the production system.

(*) "The notion of a frame was originally proposed by Minsky as a basis for understanding physical perception. On the one hand it provides a structure that unites different perceptions into a single entity, whilst on the other hand the structure of the frame makes possible the rapid interpretation of input by applying various expectations.

> More recently, the notion of a frame has evolved to name a very high level *data structure* that normally consists of a number of *slots*, some with defaults. Frames are used to represent common clusters of facts and are therefore primarily a form of *knowledge representation*. They can relate to any kind of object. For example, frames have been used to store knowledge about physical objects, *database* queries and stories. Underlying all frames is the idea that some predefined structure already exists and that the relevant instance of that structure can be first identified in some way and then be used to guide the procedure that interprets subsequent input data." [Colin Beardon, *Artificial Intelligence Terminology*, Ellis Horwood Ltd., 1989]

(5) The design aid and the creativity of a design activity

It is believed that a computer can produce a better solution out of known options, but cannot 'create' a design solution. When the prototype knowledge-based system was being developed, a fundamental development philosophy was that creativity should stay in the designers' hands. Automating the design process was, therefore, deliberately excluded from this project. The prototype system was designed not to impose a particular design solution, but, instead, to assess the designer's potential decisions from inter-disciplinary points of view, so that serious failures would be avoided during the course of the design process.

7.3 Further Work

Further work is discussed in three categories, i.e. short, middle and long term, which may be considered as one or two years, about five years, and several or more years, respectively.

7.3.1. Short term: one or two years

Improving the prototype knowledge-based system's capability

Concentrating upon daylighting and lighting design aspects, the prototype system's capability, as an information resource in particular, needs to be improved in terms of the interaction between the user (designers) and the computer design aid. Extensive use of *Leonardo*'s user interface capability, i.e. *Screen Designer* and its procedural language, should be considered. *The hypertext* facility in particular should be exploited to provide the explanation of the individual concepts comprising the building design process, i.e. each of the *design features*, *design issues*, *design tasks* (*design variables*), and the relationships between the *design variables*, in an organised manner. This could be done as explained below.

An original screen, which is displayed during the consultation in relation to a particular concept, e.g. a *design issue*, may show keywords representing its subsidiary concepts, i.e. *design tasks* associated with the *design issue*. Similarly, original screens for the *design tasks* may contain keywords which represent the design variables associated with these *design tasks*. If a *hypertext* screen is developed for each of the concepts comprising the framework, and tagged to these keywords within the original screens, the user can obtain an explanation of these subsidiary concepts by calling the *hypertext* screens via these keywords. Such *hypertext* screens themselves, meanwhile, may also contain keywords representing their subsidiary concepts, so that the user may access from one *hypertext* screen another obtaining further detailed explanations. As a result, the *hypertext* screens can be developed into three pyramids in terms of *information*, *design decision* and *performance*, in relation to the conceptual hierarchy described in Chapter 6 (see Figure 7.1 for those related to *design decision variables*), namely:

(a) *hypertext* screens regarding *design issues* (1) "*General outline of requirements*" and (3) "*Context of the scheme* (*site conditions*)", and their originating *design tasks* are associated in terms of *information* (Figure 7.2 (a));

(b) *hypertext* screens regarding the *design issues* and *design tasks* originating from the *design feature* "*development of a design solution*" are related in terms of *design decision* (Figure 7.2 (b)); and

(c) the *hypertext* screens associated with the *design aspects* of the *design issue* 2 and *performance variables* can be bound together in terms of *performance* (Figure 7.2 (c)).

These pyramids of *hypertext* screens suggest that:

(i) the user can access a *hypertext* screen that provides the information regarding a particular concept from an original screen during the session;

(ii) the *hypertext* screen accessed then becomes a "root" from which the user may track down other *hypertext* screens which explain the associated subsidiary concepts via keywords;

(iii) a *hypertext* screen explaining the concepts of higher level cannot be accessed from the "root" hypertext screen.

In such a manner, the user may obtain not only the explanatory information associated with the current concept under question, but also have a further insight regarding inter-disciplinary design working with more detailed subsidiary concepts. In addition, since the original screens for process checking (i.e., those at the bottom of the conceptual hierarchy) are associated with the relationships between *design variables*, the *hypertext* screens regarding each of the *design variables* can be accessed from them. In other words, the *hypertext* screen pyramids are "bridged" at their bottom level by these original screens related to the relationships (Figure 7.3).

From a practical point of view, the system's user interface may be improved in terms of wording as well as interface screen in general. The computer-based design aid, i.e. the prototype system, will eventually be evaluated in terms of its usability in a practical situation.

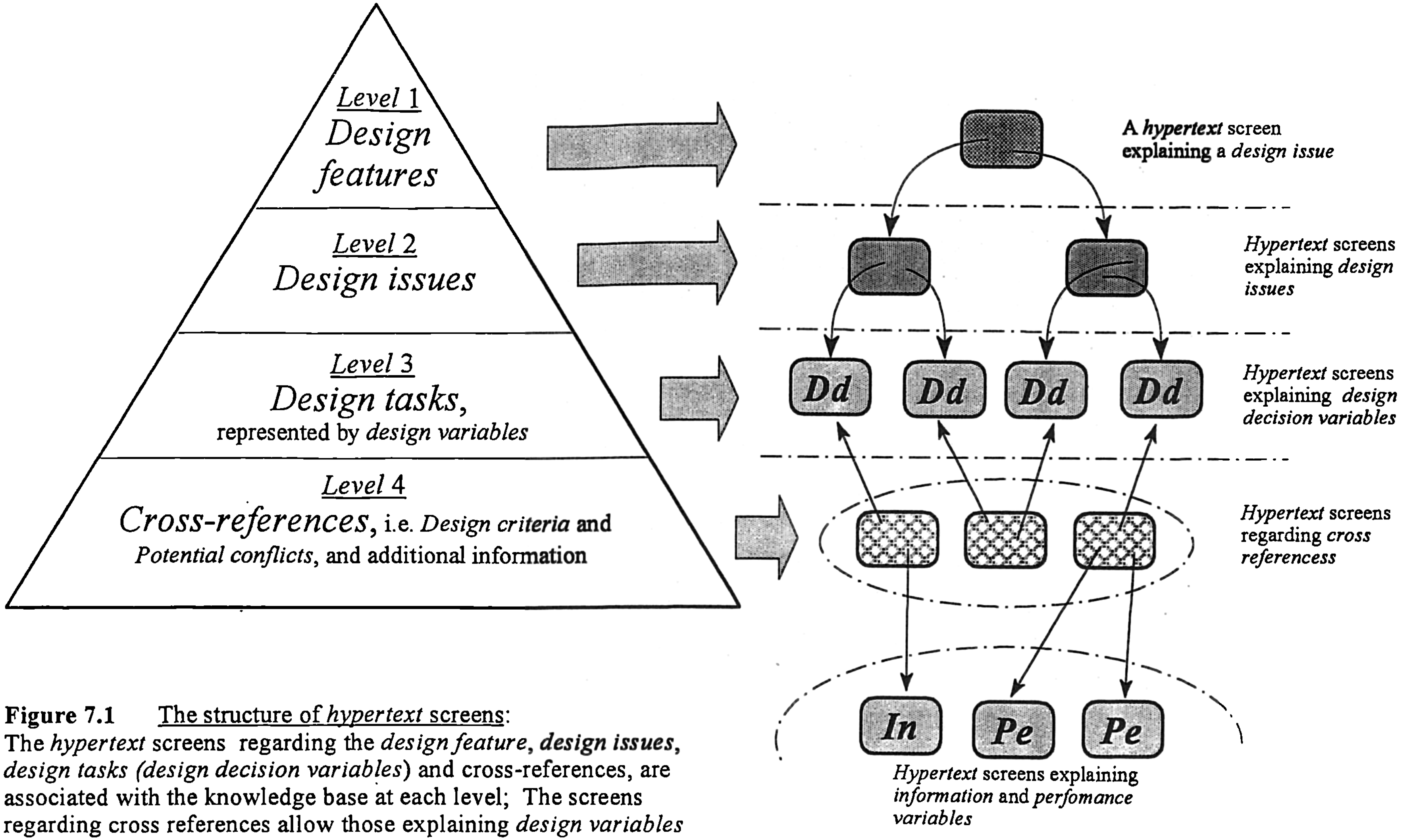
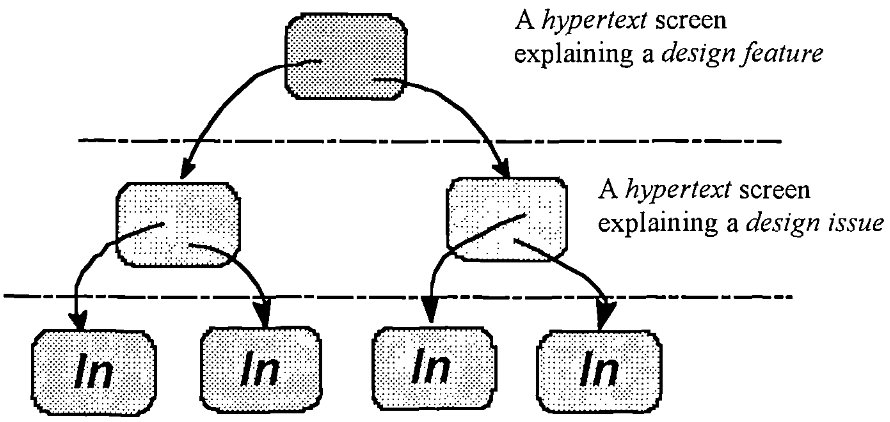
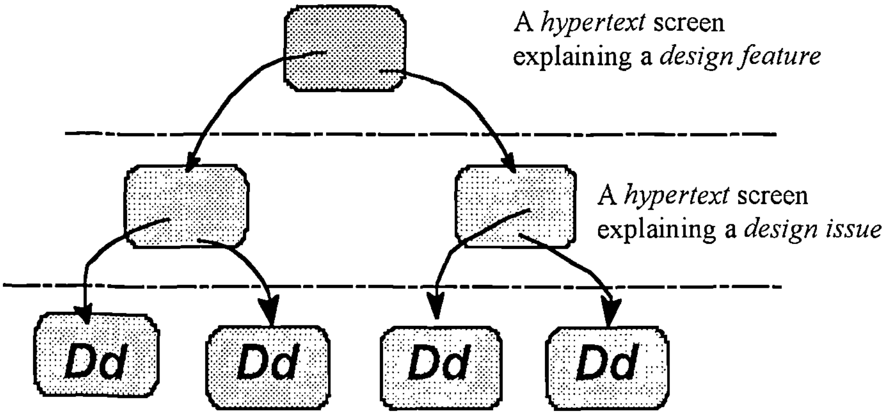


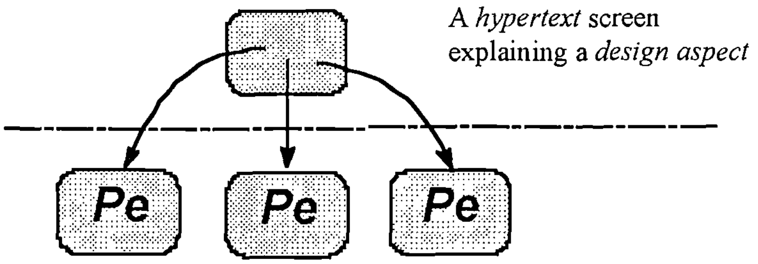
Figure 7.1 The structure of *hypertext* screens:
The *hypertext* screens regarding the *design feature*, ***design issues***, *design tasks (design decision variables*) and cross-references, are associated with the knowledge base at each level; The screens regarding cross references allow those explaining *design variables* (*Dd*, *In* and *Pe*) to be accessed.



(a) *Hypertext* screens describing *information variables*



(b) *Hypertext* screens describing *design decision variables*



(c) *Hypertext* screens describing *performance variables*

Figure 7.2 Three pyramids of *hypertext* screens in relation to *information*, *design decision* and *performance variables.*

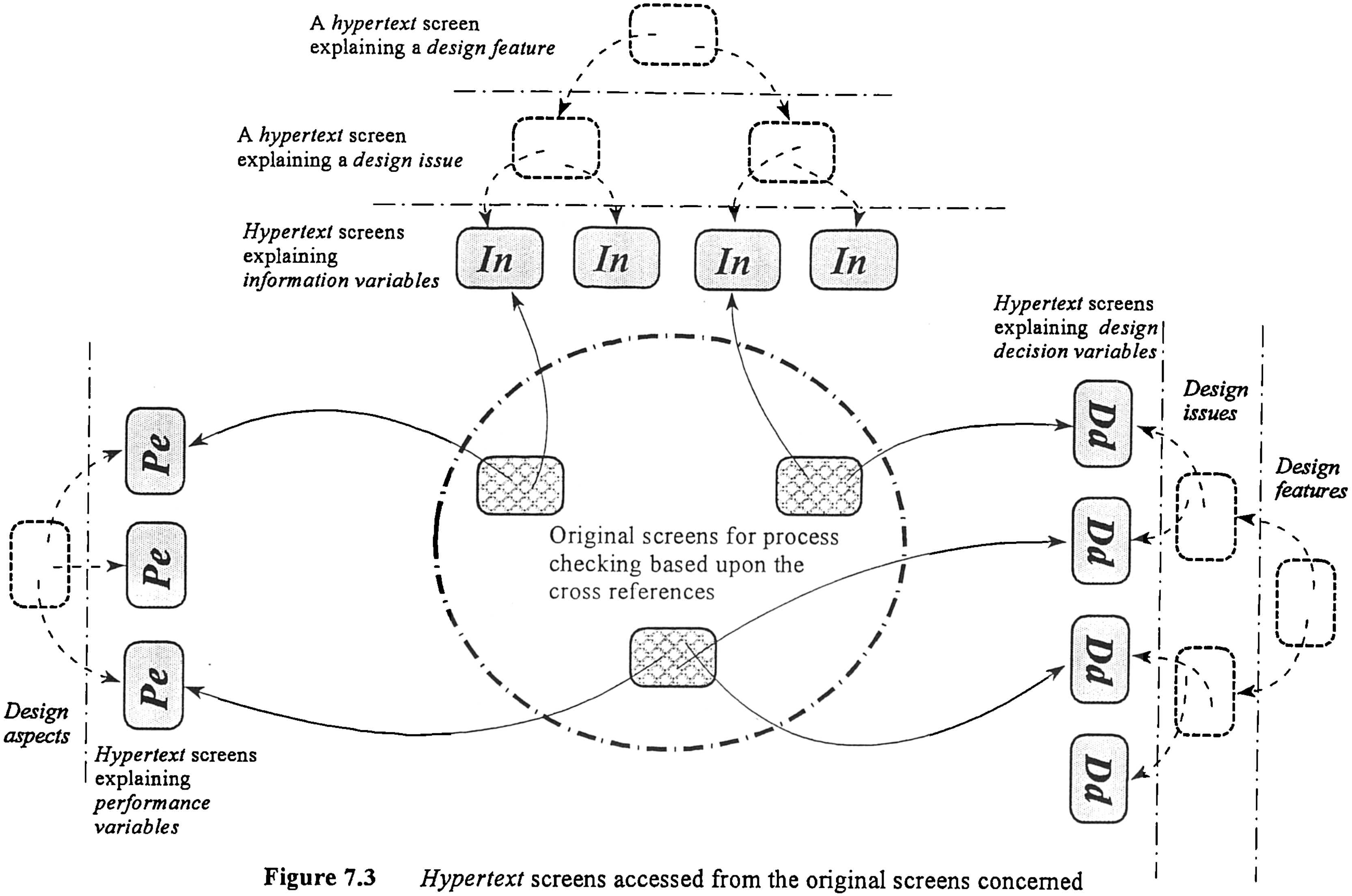


Figure 7.3 *Hypertext* screens accessed from the original screens concerned with the relationships between *design variables*.

7.3.2 Middle term: about five years

(1) *Combining an external simulation program*

It was considered that a computer-based design aid for inter-disciplinary design working should have another function which would allow the user to utilise the power of an external simulation software package within the context of the design process, rather than individually. In other words, the IKBS system may not necessarily need to have a simulation capability, but should be able to bring in the back-end processor at a pertinent stage of the design process. In order to do so, the IKBS has to be able to handle minute design data describing the design solution to be evaluated during the consultation, so that it can feed them into the external simulation program. The interface between the IKBS and a back-end processor will be another issue to tackle.

(2) *Further knowledge elicitation*

As discussed in Section 7.2, a design team (a group of designers) could be an ultimate knowledge source of inter-disciplinary design working. In this case, the design team could be consulted in terms of their experience regarding the performance of their past projects, with particular reference to failures. The knowledge obtained could be used to enhance the process checking capability of the intelligent knowledge-based system. By analysing such experience, the outcome could be added to the prototype system by modifying knowledge-base modules or adding new modules. In order to utilise this kind of experience, meanwhile, further study on knowledge representation techniques other than IF-THEN rules, may be of interest.

(3) *Study on the knowledge representation and inference*

Further study on the knowledge representation and inference mechanism should be conducted, so that stereotypes is embodied in a IKBS together with other working knowledge. The use of an object-oriented programming approach may be worthwhile exploring. IKBS techniques other than the production system should also be considered. Such alternatives could include case-based system technique and the frame theory.

(4) *Extend the subject area*

In this project, a framework and an IKBS were developed with particular reference to daylighting and lighting design aspects. In order to develop a comprehensive framework, which would include not only lighting design but also ventilation, heating system, construction, and even aesthetic points of view, individual checklists for inter-disciplinary design working could be developed with particular reference to each of these design issues. This could be done by taking the similar checklist approach to these design aspects as discussed in Chapter 4 of this thesis, i.e. identifying design variables associated with each design issue and carefully studying the inter-relationships between them.

7.3.3 Long term: several or more years

Integrated inter-disciplinary design working environment

A comprehensive framework for inter-disciplinary building design working could be developed by integrating those with particular reference to individual design aspects, such as lighting, heating and ventilation. Having design data-bases as well as being connected to back-end simulation programs, a computer-design aid may provide an integrated building design environment, as illustrated in Figure 7.4, where it would promote interactive design working between the design team members.

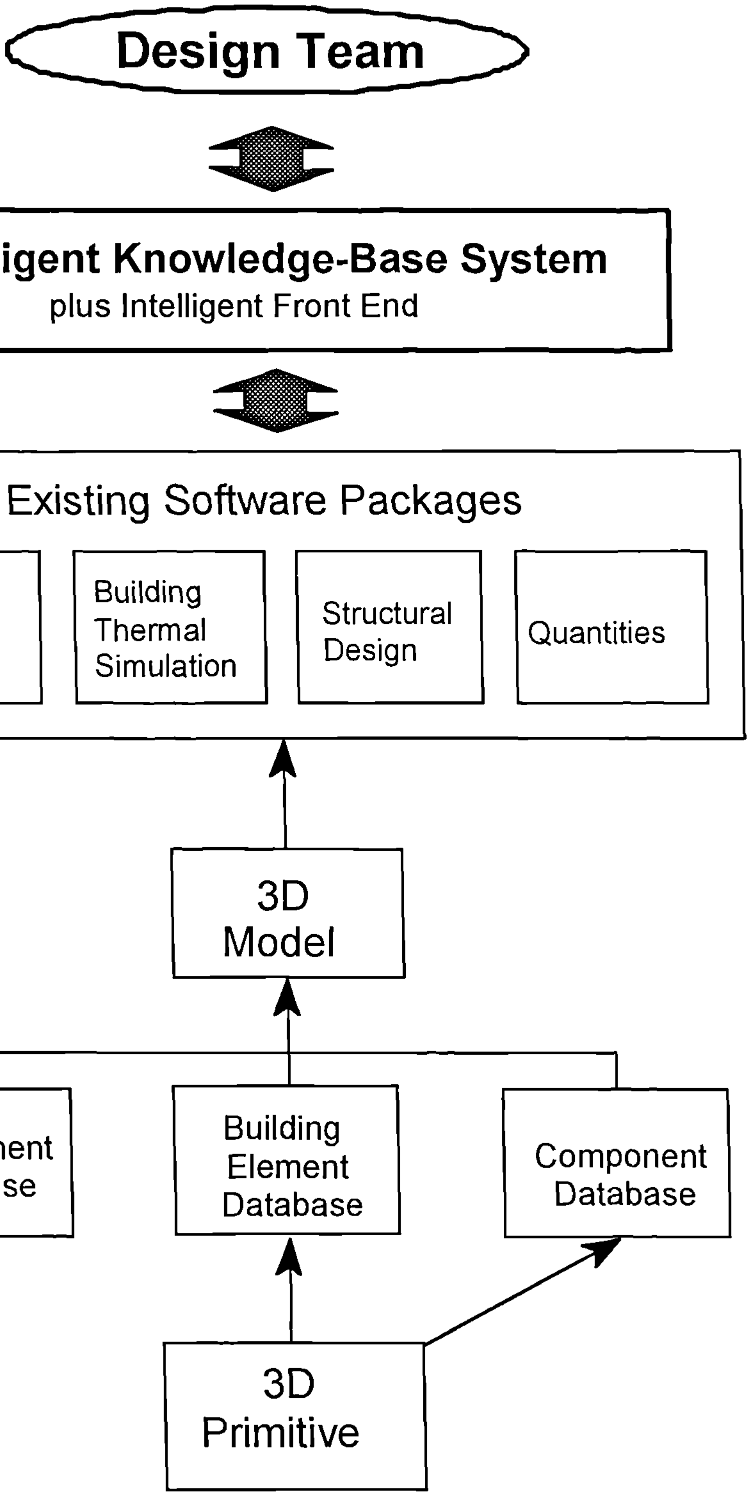


Figure 7.4 Outline of an integrated building design environment (see also Figure 1.9 of Chapter 1)

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AND

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Appendix A

Appendix A

INFORMATION USAGE IN THE ARCHITECTURAL DESIGN PROCESS

In the early '80s, research was carried out to study information use in the building design process [Mackinder and Marvin 1982, Marvin 1985a, 1985b]. It was based on a series of case studies of live design projects in architectural offices of various types, and studied the design work of individuals, rather than the corporate output of offices.

'Information' may be interpreted in a wide variety of different ways. Mackinder and Marvin described information within the context of the design decision making process as "input, data storage etc." and "the complete range of data that needs to be obtained in order to create and solve a design problem [Mackinder and Marvin 1982]." It is understood that information will be required when a designer identifies a design problem and also when he develops a solution for it.

The case studies showed that a designer generally needed information when he was looking for either:

(a) an 'answer' (factual data) which he can feed directly into his problem in order to obtain a solution, or

(b) an 'explanation' which gives him the understanding of a concept or of the application of factual data, that enables him to work out a solution.

It is thought that once a designer obtains information, in either case, he will *interpret* its value within the context of the decision making under consideration. The designer will then *examine* the information, may sometimes modify it, and either *accept* or *reject* it for use in the decision making process.

During the case studies, 'information' was observed to encompass not only written or memorized design data but also other influences on decision making. These included the experience and preferences of the designer and other persons with an interest in the project; legal and practical requirements including site conditions; and the brief. The research presented three categories of information according to its sources:

A. Outside events and agencies, and other constraints,
B. Experience, and
C. Recorded design data.

A. Outside events and agencies, and other constraints

There are conditions largely beyond the control of the designer, which are either imposed on or recommended to him. This category of information includes:

(a) client's brief,
(b) fixed physical criteria such as site conditions, energy supply, cost restrictions etc. as applied to a particular project, and
(c) statutory requirements.

General briefing and communication with clients appeared to be particularly important. The case studies observed that incomplete briefing and lack of information at an early stage of the design tended to complicate the design and to be a cause of abortive work. There were a few cases in which briefing guides developed by either the designer or client were used. Use of briefing guides was found to provide a valuable basis for the development of the design and also to prevent communication problems between the designer and client.

Needless to say, factors such as budget, project programming and site constraints were recognized as significant influences on design decision making in all the case studies. The level of information input from outside agencies seemed to cause delay and disruption during the design process. Negotiations for statutory procedures with local authorities appeared to consume a large proportion of design time.

B. Experience

It is not easy to give a clear answer to what experience really is. It may be information which "has already been acquired and is carried in the head although it needs to be sought on occasions by the designers," as the research suggested [Mackinder and Marvin 1982]. The studies on information use relied mostly on interviewing architects on 'what they think they use', rather than being able to look at what they actually do. During the case-study-monitoring interviews, the architects were found to be rather vague about what experience actually is and how it helps them. 'Experience' may have been thought of as the designer's personal knowledge which came from previous practice, from colleagues, manufacturers and clients. But sometimes designers tended to quote 'experience' as the reason for design decisions based on their background knowledge picked up during their educations and from technical publications and product data once read but now incorporated into their thinking [Marvin 1985a, 1985b].

Having analyzed the results of the interviews, the research identified three main types of experience, namely:

(1) experience of the decision making process of building design,

(2) experience of how a building is put together, and

(3) experience of performance of previous design solutions.

(1) 'Experience of the decision-making process'

This type of experience enables the designer to predict what problems may arise and to be aware of information sources which may be appropriate. Experienced designers seem able to go straight to the key issues and know which aspects of the design are likely to have an important bearing on the overall design. The designer using his experience can predict, from the outset of a project, key problems which may occur, and so abortive work can be avoided. Knowing which information sources have previously provided adequate data, helps the experienced designer to obtain a satisfactory answer more quickly than less experienced designers, who tend not only to use written references more frequently but also have to consult a wider range of sources. Experience can, consequently, speed up information retrieval and production. The experienced designer also seems better able to collect the necessary information and make design decisions in an efficient sequence. Experience, therefore, allows the designer to work more efficiently so that he can spend the time saved making further progress in the design.

(2) 'Experience of how a building is put together' is the experience understanding general knowledge of building construction gained from both education and practice. This type of experience allows the designer to make general assumptions about the form and construction of the building. This experience involves the general principles of how a building is put together and also what building forms and methods of construction are likely to be a suitable for particular uses. The experienced designer can, therefore, make design decisions in terms of what would normally be an appropriate answer to the requirements of the brief and site, without consulting a number of outside or written references, which would be immensely time-consuming.

(3) 'Experience of performance of previous design solutions' is a more straightforward type of information which involves "first or second-hand knowledge" of how a building or an element of a building performs [Mackinder and Marvin 1982]. It is mainly based on observations of building failures and of the appearance of buildings. This type of experience tends to be derived from design faults and mistakes made previously, as the designer's attention is more commonly drawn to failures than successes. Thus it is likely to be negative feedback from previous projects. This type of experience can assist in the selection of a particular form of construction or a particular component, especially during the later detailed stages.

According to the designers interviewed during the case studies, 'experience' was the most often quoted aid to making a decision, largely because it seems to be "readily available, quicker to use and more palatable for designers than most forms of information" [Mackinder and Marvin 1982]. Consequently, the designers could save time.

The first two categories of experience - experience of the decision-making process, and of how a building is put together - would appear to have definite advantages in saving time and preventing abortive work. The research found a general feeling among designers that "experience is best picked up through the practice of design." It seems likely that what designers most value is the experience of the decision-making process. The true value of designers' experience of performance, materials and construction depends on such qualities as its being reliable and up-to-date, as does the value of written data.

C. Recorded design data

This type of information includes not only published information in the form of books, trade literature, government design guides etc., but also archives kept by offices themselves. The case studies revealed a general unwillingness on the part of architects to consult written sources of information, partly due to pressure of time. Thus, use of recorded, or written, design data in the design process is limited, as it is seen as a time-consuming activity. According to the research, the majority of the written sources which the designers said they had consulted over the case-study design work, were used in order to resolve detailed aspects of design. This was usually, but not always, during the later stages of the design programmes. For the outline design, independently published data, such as design guides, building reviews in journals and information handbooks, were the main sources of reference when any were used.

The research found that written references were mainly used to check points, or to find solutions to ideas already generated by the designer. They were seldom used to spark off ideas or to predict problems. It was found that written references were more frequently used in 'one-off' design projects than in cases where the office had a history of previous design of a similar building type.

The case studies showed that where written data were consulted technical references were more frequently used than general design references. It was found that designers tended to avoid official literature such as Building Regulations and associated data unless its use was absolutely necessary, because of its complex nature. Designers preferred concise, well-illustrated literature, such as that produced by the trade associations, and they preferred to rely on trade and trade association literature and technical guides published in current journals.

Appendix B

Appendix B

DAYLIGHTING AND ARTIFICIAL LIGHTING DESIGN

This Appendix presents the current knowledge and expertise regarding daylighting and lighting design. Firstly, lighting design criteria are explained in terms of visual environment. In Section B.2, the characteristics of daylight are described in relation to daylighting design issues. Then, a window design sequence is presented in Section B.3, based upon the CIBSE Application Manual '*Window Design*'. The energy implication of artificial lighting installation is explained in Section B.4, and finally, the lighting design process is illustrated in Section B.5, based on the CIBSE *Code for Interior Lighting* and BS8206 *Lighting for Buildings*. The information presented in this Appendix was used to develop a framework, as well as an intelligent knowledge-based system, for inter-disciplinary design working with particular reference to daylighting and lighting design aspects in a later chapter.

B.1 The Functions of Lighting and Visual Environment

The lighting of an interior should fulfil three functions as follows:

(a) Safety
Lighting should ensure the safety of people in the interior by making any hazards visible;

(b) Task performance
Lighting should facilitate the performance of visual tasks by illuminating them, so that the relevant details of the tasks can be seen with ease and accuracy;

(c) Appearance and character of the visual environment
Different visual environments can be created since different aspects of lighting influence the appearance of the elements in the interior in different ways. Lighting should therefore aid the creation of an appropriate visual environment, including the mood or atmosphere of an interior.

The visual environment created in any space should be appropriate for the purpose of that space. To ensure this, due consideration should be given to these three functions, since different spaces have different functions, there is no single set of lighting recommendations which is universally applicable (each type of application having its own set of recommendations).

A visual environment designed or created is evaluated in terms of the following lighting criteria:

(1) Illuminance

The lighting level produced by a lighting installation is usually quantified by the '*illuminance*' produced on a specific plane on which the major tasks in the interior are supposed to be carried out. Since it affects both the performance of the tasks and the appearance of the space, the illuminance provided on an appropriate plane is the most widely used lighting criterion.

Here, the appropriate plane is normally assumed to be horizontal although tasks in planes in other orientations do occur.

Average illuminance produced by a lighting installation on an appropriate plane in an area typical of the application is called '*standard service illuminance*'. This is based on considerations of the performance of appropriate tasks, the comfort of the people doing the tasks, and the time for which the space is occupied. The CIBSE *Code for Interior Lighting* shows examples of activities/interiors appropriate for each standard service illuminance, shown in Table B.1. The service illuminance has been selected from following Commission Internationale de l'Eclairage (CIE) scale: 20, 30, 50, 75, 100, 150, 200, 300, 500, 750, 1000, 1500, 2000 lux. When the situation is not typical, then the standard service illuminance can be modified according to the flow chart, shown in Table B.2, to provide a *design service illuminance*.

(2) Uniformity and Illuminance ratios

The illuminance provided across a space may vary. To avoid complaints about such variation, a uniformity criterion in terms of the ratio of minimum illuminance to average illuminance (or sometimes maximum illuminance) is valuable. The ratio of the minimum illuminance to the average illuminance over the task area should not be less than 0.8 [CIBSE *Code for Interior Lighting*]. This is equivalent to a ratio of a minimum illuminance to the maximum illuminance of 0.7 [BS8206, Part 1].

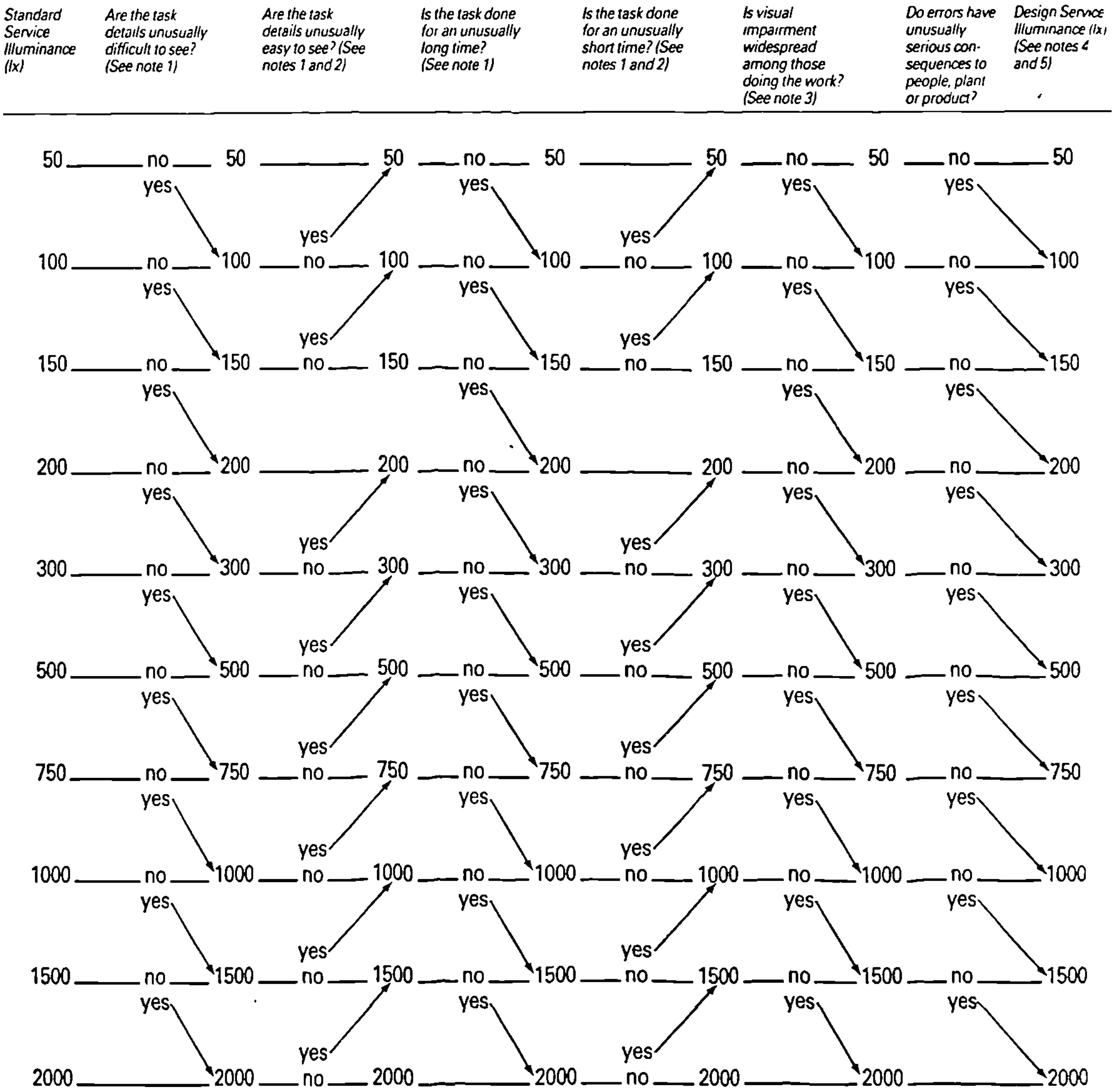
Another criterion applies to the uniformity of illuminance when working and non-working areas are adjacent. In such situations, e.g. an interior with localised or local lighting, the illuminance around the working area should not be less than one-third of that of the working area [BS8206, Part 1].

The illuminance on room surfaces other than the working plane, such as walls and ceilings, and the reflectances of those surfaces, strongly influence the appearance of the room and the comfort of the viewer as well as the ease of performance of the visual task [BS8206, Part 1]. Figure B.1 shows the recommended ranges of room surface reflectances and illuminance ratios relative to the illuminance on the working area [CIBSE *Code for Interior Lighting*, p.57]. In an interior with general lighting, the ratio of the average illuminance on the ceiling, to the average illuminance on the horizontal working plane, should be within the range 0.3 to 0.9, and the ratio of the average illuminance of any wall to the average illuminance on the horizontal working plane should be within the range 0.5 to 0.8.

Table B.1 Examples of activities/interior appropriate for each standard service illuminance (From Table 2.1 of the CIBSE *Code for Interior Lighting*)

Standard Service Illuminance (lx)	*Characteristics of the activity/interior*	*Representative activities/interiors*
50	Interiors visited rarely with visual tasks confined to movement and casual seeing without perception of detail.	Cable tunnels, indoor storage tanks, walkways.
100	Interiors visited occasionally with visual tasks confined to movement and casual seeing calling for only limited perception of detail.	Corridors, changing rooms, bulk stores.
150	Interiors visited occasionally with visual tasks requiring some perception of detail or involving some risk to people, plant or product.	Loading bays, medical stores, switchrooms.
200	Continuously occupied interiors, visual tasks not requiring any perception or detail.	Monitoring automatic processes in manufacture, casting concrete, turbine halls.
300	Continuously occupied interiors, visual tasks moderately easy, i.e. large details >10 min arc and/or high contrast.	Packing goods, rough core making in foundries, rough sawing.
500	Visual tasks moderately difficult, i.e. details to be seen are of moderate size (5-10 min arc) and may be of low contrast. Also colour judgement may be required.	General offices, engine assembly, painting and spraying.
750	Visual tasks difficult, i.e. details to be seen are small (3-5 min arc) and of low contrast, also good colour judgements may be required.	Drawing offices, ceramic decoration, meat inspection.
1000	Visual tasks very difficult, i.e. details to be seen are very small (2-3 min arc) and can be of very low contrast. Also accurate colour judgements may be required.	Electronic component assembly, gauge and tool rooms, retouching paintwork.
1500	Visual tasks extremely difficult, i.e. details to be seen extremely small (1-2 min arc) and of low contrast. Visual aids may be of advantage.	Inspection of graphic reproduction, hand tailoring, fine die sinking.
2000	Visual tasks exceptionally difficult, i.e. details to be seen exceptionally small (<1 min arc) with very low contrasts. Visual aids will be of advantage.	Assembly of minute mechanisms, finished fabric inspection.

Table B.2 Flow chart for obtaining the design service illuminance from the service illuminance (From Table 2.2 of the CIBSE *Code for Interior Lighting*)



Notes

1 The standard service illuminances recommended in the schedule are based on tasks which are representative of their type in the detail that has to be seen and the time for which the task has to be done. These steps in the flow chart allow for departures from these assumed conditions.

2 The standard service illuminance of 200 lx is provided as an amenity for continuously occupied interiors, even when perception of task detail is not required.

3 If the cause of visual impairment is dirty or scratched spectacles, safety glasses, safety screens, etc., it may be more effective to clean or replace these items rather than change the lighting. If safety screens are acting as a source of veiling reflections then the lighting/task/worker geometry should be re-arranged.

4 If the design service illuminance is more than two steps on the illuminance scale above the standard service illuminance, consideration should be given to whether changes in the task details, the organisation of the work or the people doing the work are more appropriate than changing the lighting.

5 For a design service illuminance of 1500 lx or 2000 lx, local lighting supplemented by optical aids should be considered.

(3) Surface reflectance

In a large room the contribution of light reflected from the ceiling to the total illuminance on the working plane is usually large and the ceiling occupies a substantial proportion of the visual field. For interiors lit from the ceiling, the significance of the ceiling reflectance increases as the room area increases. Therefore, the reflectance of the ceiling cavity of large rooms should be at least 0.6 (see Figure B.1); this will usually mean that the reflectance of the paint or other surface finishes must be at least 0.8.

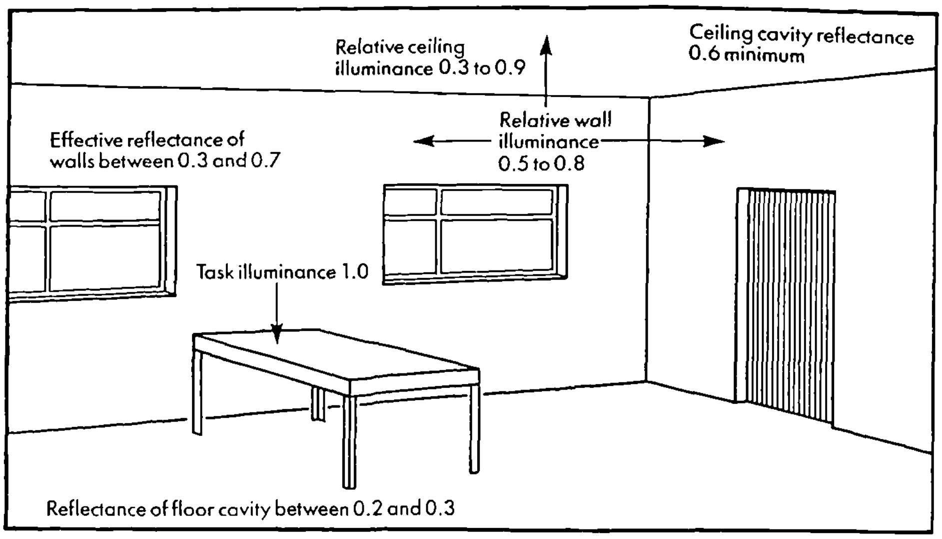


Figure B.1 Recommended illuminance ratios and surface reflectances (From Figure 2.1 of the CIBSE *Code for Interior Lighting*)

Wall reflectance, meanwhile, is usually unimportant to the lighting of a large room except for the area immediately near to the walls. In small rooms, however, wall reflectance is always important as walls with high reflectance will enhance the illuminance on the working plane and increase the inter-reflective component of the lighting, thereby increasing uniformity. The importance of having a high wall reflectance is increased when the room is predominantly lit by daylight from side windows. The use of high reflectance wall finishes should be treated with caution, however. Large areas of high reflectance may compete for attention with the task areas and may lead to eyestrain and feelings of discomfort. Further, if the high reflectance surfaces are produced by gloss paint, reflected glare is likely to occur. In working interiors, the effective reflectance of the principal walls should be between 0.3 and 0.7, as shown in Figure B.1. This usually means that wall surface finishes should have an actual reflectance greater than 0.5.

(4) Glare

"Glare is the discomfort or impairment of vision experienced when parts of the visual field are excessively bright in relation to the general surroundings" [CIBSE *Code for Interior Lighting*]. The most common sources of excessive brightness are luminaires and windows, seen directly or by reflection. Glare can have two effects: it can impair vision, in which case it is called '*disability glare*'; and it can cause discomfort, in which case it is called '*discomfort glare*'.

Disability glare is most likely to occur when there is an area close to the line of sight which has a much higher luminance than the object of regard. Then, scattering of light in the eye and changes in local adaptation can cause a reduction in the contrast of the object. This reduction in contrast may be sufficient to make important details invisible and hence may influence task performance. Alternatively, if the source of high luminance is viewed directly, noticeable after-images may be created. The most common sources of disability glare indoors are the sun and/or sky seen through windows and electric light sources seen by reflection. Care should be taken to avoid disability glare in interiors by providing some method of screening windows and avoiding the use of highly specular surfaces [CIBSE *Code for Interior Lighting*, p.18].

The discomfort glare, on the other hand, occurs when the range of luminances within the field of view is too large [BS8206, Part 1]. A possible cause of discomfort in an interior is glare from the luminaires. The degree of discomfort experienced will depend on:

(i) the luminance and size of the glare source,
(ii) the luminance of the background against which it is seen, and
(iii) the position of the glare source relative to the line of sight.

The effect of all these factors has been combined in a system developed by the IES (Illumination Engineering Society, now the CIBSE) to form a '*Glare Index*' [CIBSE Code for *Interior Lighting*, appendix 5]. By calculating this, the likelihood of discomfort glare being experienced in any proposed lighting installation can be estimated. As a general rule, discomfort glare can be avoided by the choice of a luminaire and its position, and the use of high reflectance surfaces for the ceiling and upper wall.

(5) Modelling / Directional effect

The directional distribution of light in a space is important to the appearance of objects and, consequently, for task performance as well as the perception of the space. The strength of directional lighting at a point can be quantified by the ratio of the magnitude of the illumination vector to the scalar illuminance (see CIBSE Code for *Interior Lighting*, Appendix 1). This quantity is known as the '*vector / scalar ratio*'. The direction of the flow of light is given by the direction of the illumination vector. No single value of vector/scalar ratio is right for all purposes but, for general use where the perception of faces is important, vector/scalar ratios in the range between 1.2 and 1.8 will be satisfactory. There is some evidence that directions of the illumination vector in the range of 15°- 45° from the horizontal are preferred. This condition can be readily achieved in rooms lit during daytime by side windows but is very difficult to achieve at night when the only electric lighting is ceiling mounted, so the vector direction is almost always vertically downward. The effect of the directional distribution of light on an object can be described in terms of the illuminance pattern, the highlight pattern and the shadow pattern, but no complete description of the way in which lighting affects the appearance of objects has yet been developed.

(6) Colour properties of light

Light sources, both natural and artificial, have two colour properties related to the spectral composition of their emission: (1) the *apparent colour* of the light that the source emits; and (2) its ability to render the colours of surfaces, i.e. '*colour rendering property*'.

The apparent colour of the light emitted by a near white source can be indicated by its *correlated colour temperature* (CCT). Each lamp type has a specific correlated colour temperature, but for practical use the correlated colour temperatures have been grouped into three classes by the Commission International de l'Eclairage (CIE), as shown in Table B.3. The choice of an appropriate apparent colour of light source for a room is largely determined by the function of the room and the impression it is required to create. The only general rules to help with the selection of apparent colour are:

(i) for rooms lit to an illuminance of 300 lux or less, a warm or intermediate colour is preferred;

(ii) cold apparent colour lamps tending to give rooms a gloomy appearance at such illuminance; and

(iii) different apparent colour lamps should not be used haphazardly in the same room.

The ability of a light source to render colours of surfaces accurately can be conveniently quantified by the CIE *general colour rendering index.* This index is based on the accuracy with which a set of test colours are reproduced by the lamp of interest, relative to how they are reproduced by an appropriate standard light source: perfect agreement being given a value of 100. Each lamp type has a specific CIE general colour rendering index, but for practical use they can be divided into a number of groups. Table B.4 shows the groups of the CIE general colour rendering index.

Table B.3 Correlate colour temperature (CCT) Classes
[CIBSE *Code for Interior Lighting*, 1984, page 17, Table 1.1]

Correlated Colour Temperature (CCT)	CCT Class
$\text{CCT} \leq 3300\text{K}$	*Warm*
$3300\text{K} < \text{CCT} \leq 5300\text{K}$	*Intermediate* *
$5300\text{K} < \text{CCT}$	*Cold*

* This class covers a large range of correlate colour temperatures. Experience in the U.K suggest that light source with correlated colour temperatures approaching the 5300K end of the range will usually be considered to have a 'cool' colour appearance.

Table B.4 Colour rendering groups used in CIBSE Code for *Interior Lighting* [CIBSE *Code for Interior Lighting*, 1984, p.17]

Colour rendering groups	CIE general colour rendering index (*Ra*)	Typical application
1A	$Ra \geq 90$	Wherever accurate colour matching is required, e.g. colour printing inspection.
1B	$80 \leq Ra < 90$	Wherever accurate colour judgements are necessary and/or good colour rendering is required for reasons of appearance, e.g. shops and other commercial premises.
2	$60 \leq Ra < 80$	Wherever moderate colour rendering is required.
3	$40 \leq Ra < 60$	Wherever colour rendering is of little significance but marked distortion of colour is unacceptable.
4	$20 \leq Ra < 40$	Wherever colour rendering is of no importance at all and marked distortion of colour is acceptable.

Where work involving accurate colour judgement is to be done, electric light sources with high CIE general colour rendering indices (i.e. from Group 1A or 1B) are necessary. Light sources with good colour rendering properties (Groups 1A and 1B), make surfaces of objects render the colours present more accurately than light sources with moderate or poor colour rendering properties (Groups 2, 3 and 4). In addition, light sources with poor colour rendering properties may distort some colours to a marked extent. Thus, where an accurate colour appearance is desirable, lamps with good colour rendering properties are appropriate.

(7) Veiling reflections

Veiling reflections occur when high luminances are reflected from a specular surface towards the observer, e.g. from the pages of a glossy magazine. The common solutions to this problem are either to use matt surfaces where possible, e.g. on desks, or to change the angle of viewing and/or the surface from which the reflection occurs so that there is no longer a high luminance object at the mirror angle to the observer. This phenomenon can still occur to some extent, even when the task material is not particularly glossy, therefore it is essential that similar care is taken over the incidence and viewing angles with most materials.

(8) Visible flicker

Cyclic light fluctuations are inherent in all light sources operated on an a.c. supply. They are usually so small as to be unnoticeable as flicker. However, sometimes the light fluctuations from discharge lamps, usually towards the end of the lamp life, become noticeable as flicker, and they can create considerable discomfort. Lamps which are producing visible flicker should be changed. Even if these cyclic light fluctuations are not themselves visible as flicker, they can produce a stroboscopic effect and give a false impression of the speed and direction of rotating objects.

B.2 Daylight and Daylighting

The value of daylight goes beyond the illumination of tasks: a daylit room varies in brightness with time; colours are rendered well; architectural form and surface texture can be enhanced by the direction of illumination. Daylight can be used for enhancing the overall appearance of interior, and illumination of visual tasks.

Daylight is the combination of *sunlight* and *skylight*. Sunlight is a part of solar radiation that reaches the earth's surface as parallel rays after selective attenuation by the atmosphere, whereas skylight is a part of solar radiation that reaches the earth's surface as a result of scattering in the atmosphere [BS8206, Part 2]. Sunlight and skylight are both important in general room lighting, but they differ greatly in their qualities: sunlight gives patches of high illuminance and strong contrasts; adequate skylight, on the other hand, ensures that there is not excessive contrast between one area of the room and another, or between the interior and the view outside. This section presents the design issues associated with the characteristics of these two components of daylight.

B.2.1 Sunlight

(1) General

Sunlight should be admitted to enhance the overall brightness of interiors with patches of high illuminance, unless it is likely to cause thermal or visual discomfort to the users, or deterioration of materials. It could also provide useful solar gain during winter months. The long-term average of the total number of hours during the year in which direct sunlight reaches the unobstructed ground is called 'probable sunlight hours' [BS8206, Part 2]. Interiors in which the occupants have a reasonable expectation of direct sunlight should receive at least 25 % of probable sunlight hours. At least 5 % of probable sunlight hours should be received during the winter months.

Uncontrolled sunlight is unacceptable, however, in most types of building. Generally, sunlight should not fall on visual tasks or directly on people at work. It is essential that the admission of sunlight is controlled in all work spaces and other interiors where the thermal or visual consequences might lead to personal discomfort or the deterioration of materials. In general, the best control of sunlight penetration is achieved by careful planning of the orientation and position of rooms and their windows. The orientation of windows should take into account the periods of occupancy and any preferences for sunlight at particular time of day [BS8206, Part 2, Clause 5.2]. Considerations of sunlight should influence the form of the building for the early stages of design, because incorrect decisions about the orientation of rooms or the geometrical shape of the building may cause excessive overshadowing of surroundings or preclude the admission of sunlight.

(2) Solar protection

All fenestration in positions where sunlight could cause discomfort or damage should be provided with solar protection, but shading devices may interrupt the view and restrict natural ventilation [BS8206, Part 2, Clause 8]. The appropriate form of solar protection will depend on whether the discomfort is mainly thermal or visual. If both, some combination of screening measures may be needed.

(a) Solar protection for thermal discomfort

For some interiors, solar gain is acceptable if sunlight is restricted during the warmer months by shading the apertures with elements such as balconies, overhang roofs, or by fixed louvres or screen. Retractable and adjustable shading is often appropriate to the low solar altitudes of the UK. Low transmission 'solar' glazing will diminish light as well as solar gain, and is the best method of reducing summer cooling loads where large areas of glass are needed for view or appearance.

(b) Solar protection for visual discomfort

Glare from direct sunlight, or from sunlight reflected in glossy external surfaces, for example, should also be controlled with shading devices. Protection may be fixed or movable. Although fixed baffles can simplify maintenance and ensure tidier facade, movable protection is generally preferable in the UK as it causes less obstruction to daylight and view on dull days [CIBSE *Code for Interior Lighting*, Section 4.4]. It is important that the system should be easily maintained and, if manually controlled, easily operated. It may be possible to arrange fixed shading devices or install prismatic glazing so that daylight is redistributed to better effect, but all fixed devices reduce the skylight admitted, and glazed area may need to be increased. The use of tinted glazing can affect colour perception. Care should therefore be taken in the use of tinted glazing materials when safety or task performance requires good colour recognition [BS8206, Part 2, Clause 5.8].

Flow charts for selecting solar protection is shown in Figure B.2 (a) and (b) [CIBSE Code for *Interior Lighting*, Section 4.4]. A means of selecting a suitable shading device depending on the problem to solve is also described in Section B12 of the Application Manual "*Window Design*" [CIBSE, 1987].

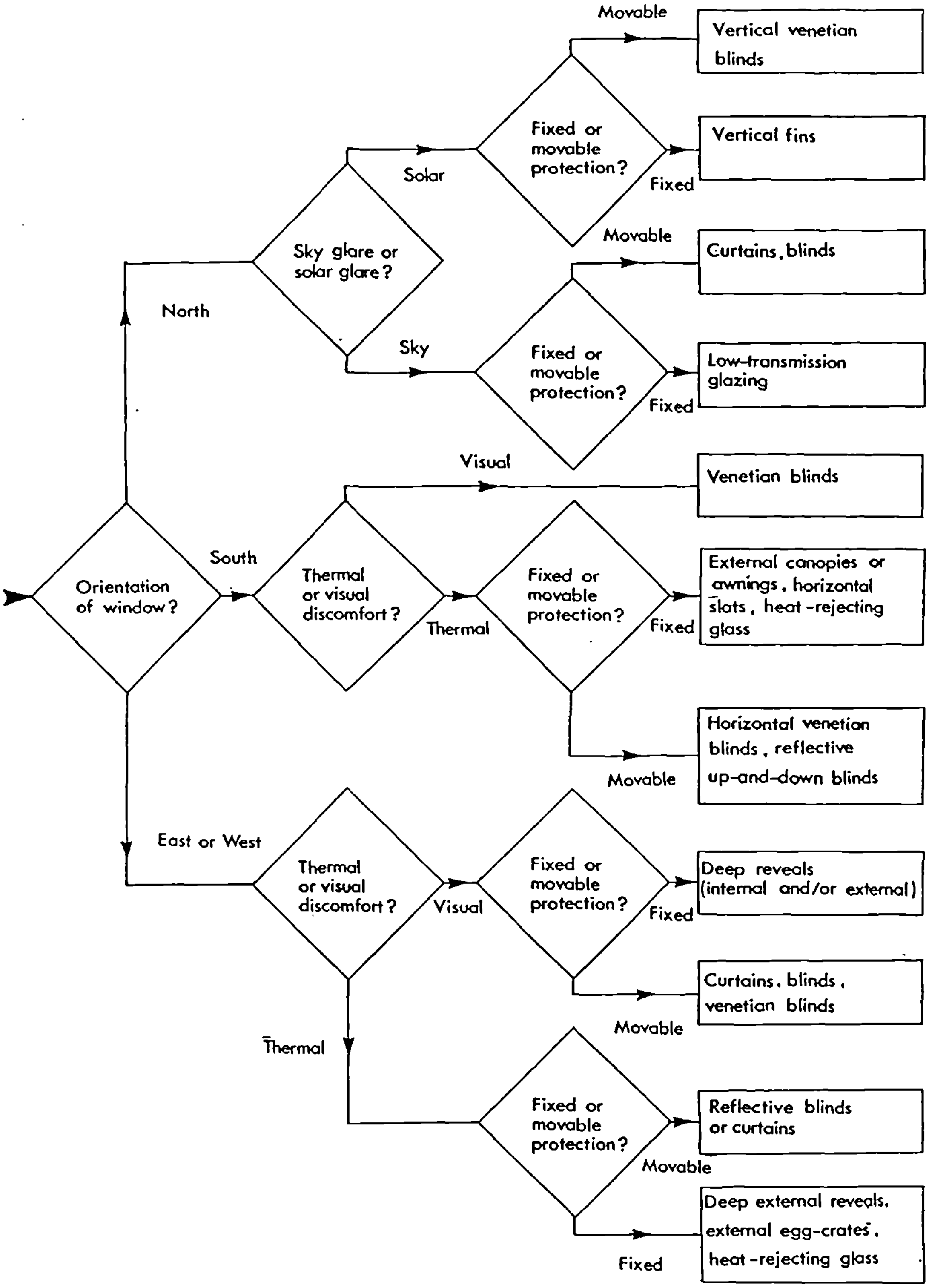


Figure B.2 (a) A flow chart for selecting solar protection for windows (from Figure 4.5 (a) of the CIBSE *Code for Interior Lighting*)

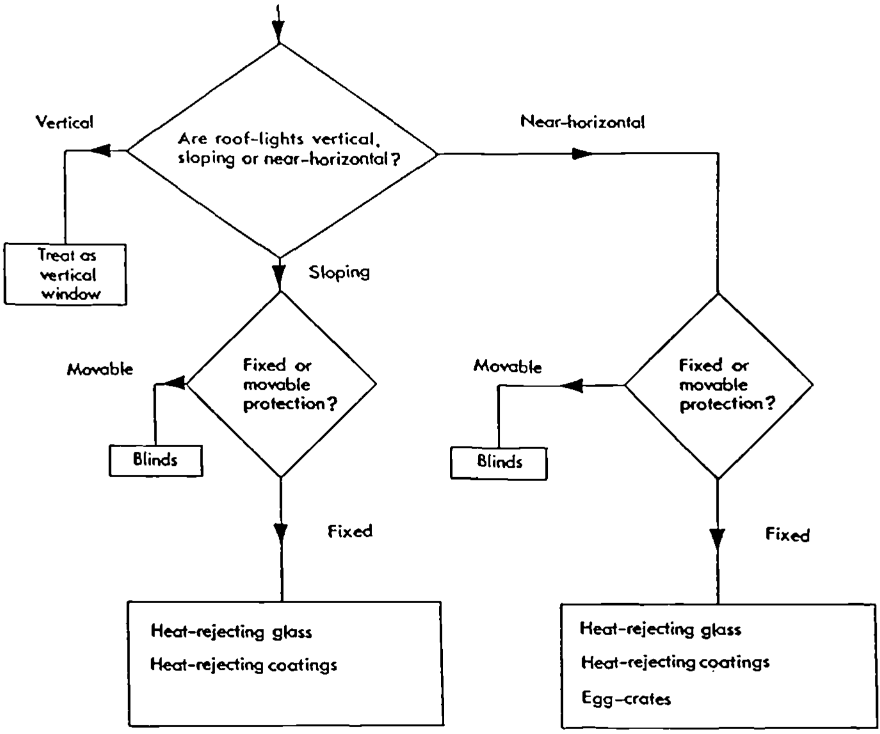


Figure B.2 (b) A flow chart for selecting solar protection for rooflights (from Figure 4.5 (b) of the CIBSE *Code for Interior Lighting*)

B.2.2 Skylight

(1) General

The user's perception of the character of a daylit interior (often described in terms like "bright and well-lit', or 'gloomy') is related to the brightness of all the visible surfaces. This overall luminance depends on the quantity of light admitted and the reflectance of interior surfaces. The reflected light within the room is as important as the direct illumination [BS8206, Part 2, Clause 5.1].

(2) Daylight factor

Due to the fact that the level of sky illumination varies considerably throughout the day and year, with the elevation of the sun in the sky and with the thickness of the cloud cover, '*daylight factor*' has been seen to be the basic measure of daylight [Hopkinson, 1963]. The CIBSE Application Manual *Window Design* [CIBSE, 1987] describes the daylight factor as "the illuminance received at a point indoors, from a sky of know or assumed luminance distribution, expressed as a percentage of the horizontal illuminance outdoors from an unobstructed hemisphere of the same sky." Direct sunlight is excluded for both values of illuminance. By following out simple means of calculation, it is possible to determine the daylight factor at any point in a room (see the CIBSE Application Manual *Window Design* [1987], Section B6, for example), and hence to draw equal daylight factor contours showing how daylight is penetrating into the room (see Figure B.3). Such a set of contours can be used to show how windows can be designed in relation to their lighting characteristics.

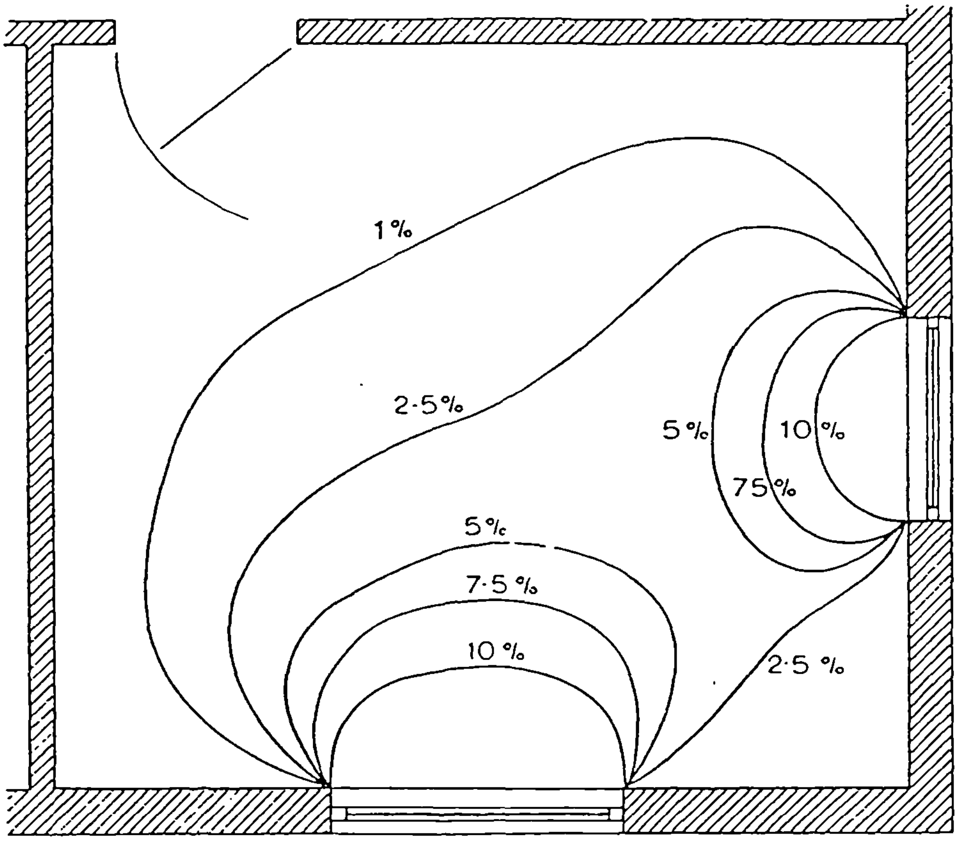


Figure B.3 Typical contours of equal daylight factor for a room with windows in adjacent walls (from Hopkinson, R.G., *Architectural Physics: Lighting* [1963], Figure 4.2, pp.31)

(3) Average daylight factor

Average daylight factor, the spacial average of daylight factors over a reference plane or planes, is widely used as the measure of general illumination from skylight [Application Manual *Window Design*, CIBSE, 1987]. Where a predominantly daylit appearance is wanted, the following criteria should be adopted [BS8206, Part 2, Clause 5.5]:

(a) Interiors without supplementary electric lighting:
If electric lighting is not normally to be used during daytime, the average daylight factor should not be less than 5 %;

(b) Interiors with supplementary electric lighting:
If electric lighting is to be used throughout daytime, the average daylight factor should not be less than 2 %.

(4) Uniformity and room depth

The interior of a room will appear gloomy not only if the total quantity of light entering is too small, but also if its distribution is poor. If an interior is too deep, in relation to the height of the window head above the floor, for example, it cannot be satisfactorily daylit even if the average daylight factor satisfies the criteria above-mentioned. This is likely to occur in a deep side-lit interior when the depth of the room, from window to back wall, is greater than the limiting depth calculated from the expression (see Figure B.4):

$$D = \frac{2wh}{(h+w)(1-R_B)} \qquad \textbf{(B.1)}$$

where D = limiting depth

w = width of room measured from side to side, parallel to window (see Figure B.4),

h = height of window head above floor (see Figure B.4),

R_B = area-weighted average reflectance of surfaces in the half of the room remote from window.

Further, a side-lit room having smaller depth than the limiting value will still look unevenly lit if part of the working surface lies beyond the *no-sky line* (see Figure B.5).

In the case of rooflights, meanwhile, unsatisfactory variation in general lighting occurs when the distance between adjacent openings is large in comparison with the ceiling height. The maximum acceptable ratio between rooflight spacing and ceiling height depends on the type of rooflight.

(5) Contrast between the interior and the view outside

Glare from windows can arise from excessive contrast between the luminance of the visible sky and that of the interior surfaces within the field of view. To avoid such glare, the window walls, the window reveals, and the interior surfaces adjacent to rooflights should be of high reflectance. In addition, glare from the sky and bright external surfaces can be reduced by:

- providing additional illumination on the window wall, from other windows or form electric lighting;
- reducing the luminance of the sky as seen from the interior, with translucent blinds, curtains or tinted/solar-control glazing; or
- splaying window reveals, to give a large area of intermediate brightness between the exterior view and the window wall.

The aim should be to achieve a subtle gradation of luminance from the darker parts of the room to the visible sky [BS8206, Part 2, Clause 5.8].

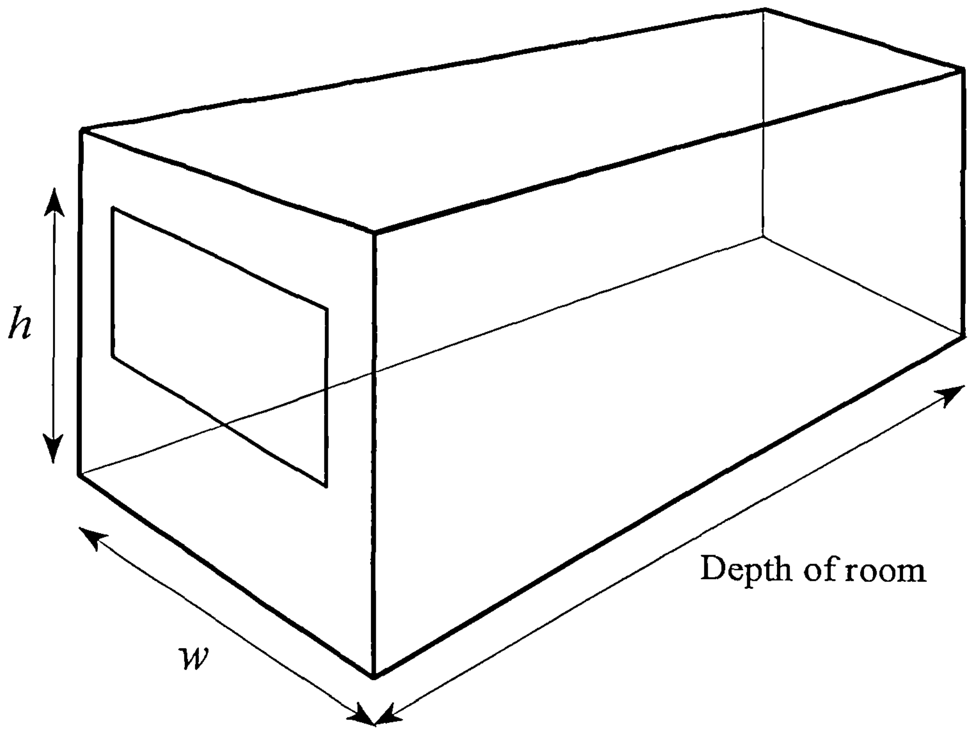


Figure B.4 Limiting depth of a side-lit room

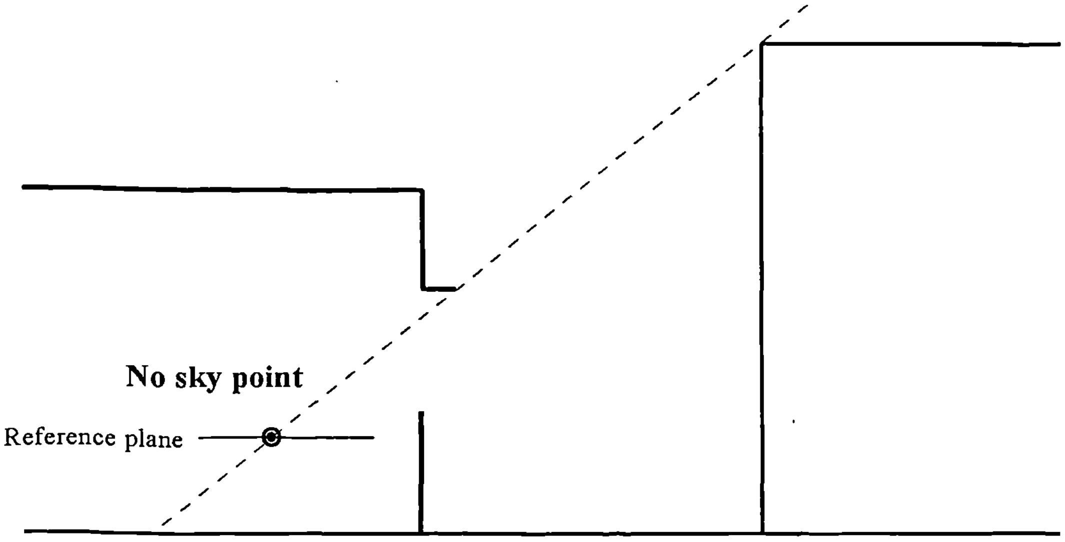


Figure B.5 The no-sky line, which is the locus of points in the reference plane delineating the area from which no sky can be seen.

B.3 Window Design Sequence

Adequate daylighting design is achieved via a sensible window design. Since windows have several functions and effects, involving provision of view outside, the building's thermal behaviour related to heat loss and solar gain, natural ventilation, the architectural appearance of the building, and so on, designing windows have to be treated within the context of a whole building design. In this section, a window design sequence is described in three steps, based on the CIBSE Application Manual "*Window Design*".

B.3.1 STEP 1: Site constraints and building form

Design approaches, i.e. priorities on various aspects of the design, and site conditions will affect the window design as well as the form of the building being designed.

(1) Priorities

The priorities accorded to access to daylight and sunlight vary from one project to another. But, in view of their importance, it is recommended that they be appraised at the initial exploratory stage of design [Application Manual, p.1]. Review the anticipated requirements of the accommodation for daylight, sunshine, view, ventilation and sound insulation as follows:

(1.a) Daylight priorities

Establish whether daylight is:

(i) *Essential*, i.e necessitating roof-lighting or shallow side-lit interiors with plan form and siting offering minimal external obstruction;

(ii) *Desirable*, i.e. daylight is preferred but supplementary artificial lighting during daylight hours will be acceptable;

(iii) *Unimportant*, i.e. plan form and siting are virtually unrestricted by daylight considerations; or

(iv) *To be restricted/excluded*, i.e. specific requirements may operate which call for the control or avoidance of daylight.

(1.b) Sunshine priorities

Orientation for sunshine must usually be balanced against other requirements. Surrounding buildings or other topographical constraints will reduce the potential maximum. The designer must seek the best compromise by reference to sun-path diagrams and bear in mind any recommendations for minimum duration.

(i) Limitation will generally be needed at some time of the day and year. Some forms of permanent screening may be acceptable, but adjustable screening will allow maximum access of daylight on dull days.

(ii) When sunshine is to be permanently excluded, glazing should preferably be oriented due north although shading will still be required to exclude morning and evening sunshine during the summer half of year.

(1.c) View priorities

The activity within a particular space or the nature of the external scene may make the provision of view:

(i) essential,
(ii) desirable,
(iii) unnecessary or undesirable.

Unless an activity requires the exclusion of daylight, a view out-of-doors should be provided irrespective of its quality. If view requirements constrain orientation, examine compatibility with requirements for sunshine.

(1.d) Ventilation priorities

Air change and movement, particularly for summer comfort, can be effectively achieved by openable windows. However, room depth (if the space is lit from one side) may preclude natural ventilation, or external noise level may demand fixed glazing. When fenestration is fixed or must remain unopened, it is particularly important, unless facing north, that glass area should be shaded and of an appropriate area. Under these circumstances, it may prove difficult to achieve adequate daylighting at all times.

(1.e) Sound insulation priorities

Current or potential external ambient noise levels may call for precautions against intrusion, or internally generated noise may need to be contained within the building. If restricted and fixed fenestration is considered for either of these situations, consider also the implications for lighting and ventilation.

(2) Site constraints

The ambient environment, including surrounding development, usually constraints building form, siting and orientation. These constraints have consequences for fenestration and may determine the extent to which the development can be naturally lit or receive direct sunlight [Application Manual *Window Design*, p.2-4].

(2.a) Planning directives

Planning directives may confine the building envelope within:

- predetermined building lines,
- height restrictions.

(2.b) Fire precautions

In some circumstances the amount of glazing in extend walling, i.e. window apertures, may be restricted to reduce the risk of the spread of fire to adjoining property by heat radiation should the building be ablaze [CIBSE Application Manual *Window Design*, p.2].

(2.c) Adjoining owners

The needs and legal rights of adjoining owners, such as rights to light, rights to sunshine, and privacy, must be recognized. These may constrain built form near site boundaries.

(2.d) Topographical constraints

The effectiveness of the fenestration is limited by obstructions, natural or man-made, present or future. Examine the topography of the site and its surroundings for existing or potential obstruction to sunshine and daylight bearing in mind the effects of sloping ground and height above ground the receipt of sunshine.

(2.e) Ambient environment

Ambient noise levels and the atmospheric environment have consequences for glazed area, window design and maintenance and on the opportunity for natural ventilation.

The ambient environment should be reviewed, in terms of such as atmospheric pollution, wind and precipitation, for conditions which may call for reduced glass or fixed windows and which may have consequences for the choice of architectural form. Shallow day-lit rooms facing a south direction whose windows must be permanently closed may need air conditioning to establish comfortable conditions in summer.

(3) Building Form and Siting

In exploring the massing and siting of alternative plan arrangements, the consequences for daylighting need to be assessed broadly and quickly; similarly the consequences for the receipt of sunlight and overshadowing of surroundings.

(3.a) Access to skylight

To ensure the full daylighting of work spaces the fenestration and external obstruction should be such that a direct view of some sky is available to the whole of the reference plane [CIBSE Application Manual *Window Design*, p.5].

The luminous flux entering a window is approximately proportional to the vertical angle θ subtended by the sky visible from the centre of the window (Figure B.6). The effective value of θ is determined by decisions made at this stage on the siting and massing of the proposed building. The block layout is effectively determined very early in the design process, usually before fenestration can be considered at all. High obstructions (small θ) necessitate a large window area to achieve a given daylight factor.

(3.b) Access to sunlight

Confirm that the requirements for access to (or exclusion of) sunlight can be achieved in the layout under consideration.

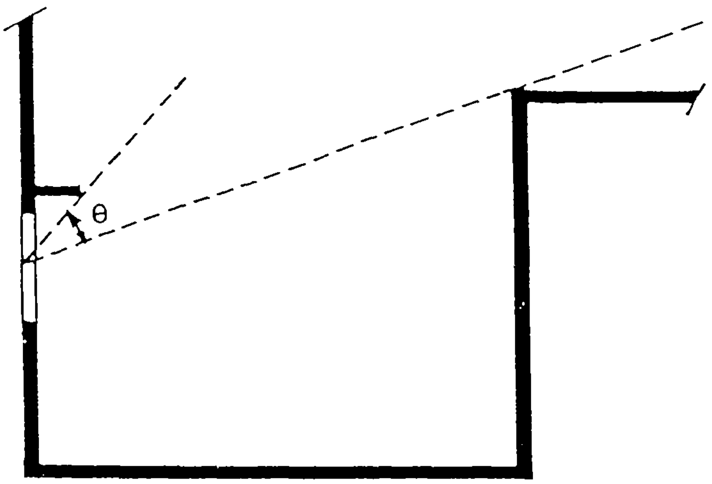
(3.c) Overshadowing

Consider overshadowing by the proposed building form. Consider whether the overshadowed area can be diminished or arranged to occur at times of least inconvenience. Can building height, plan shape, profile or orientation be amended without detriment to the desired standard of daylight, sunlight, or view? To examine the extent of shadowing and the consequences of change in building position and profile, consider:

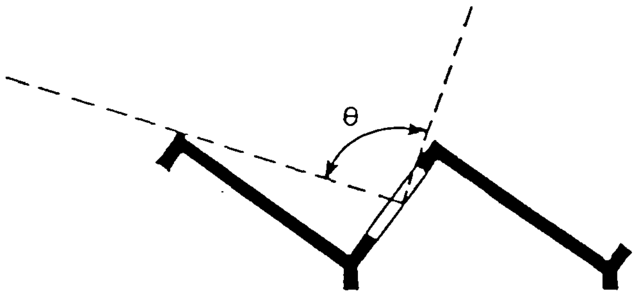
(i) Plan form of cast shadows at selected critical times.

(ii) Checks on potential sunlight availability at selected critical places.

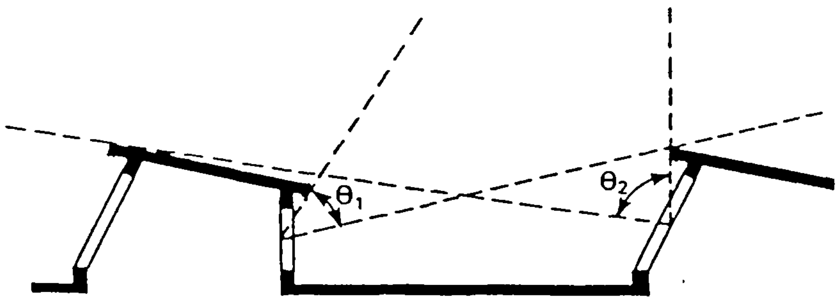
(iii) Model studies, permitting review of potential daily shadow pattern at chosen times of the year.



(a) Side window



(b) Sawtooth



(c) Monitor

Figure B.6 The angle of sky (θ) subtended in the vertical plane normal to the window seen from the centre of the window. (from Figure A1.2 of CIBSE Application Manual *Window Design*, pp.6)

(3.d) Thermal consideration

Full daylighting may have unacceptable thermal consequences but rational decisions on fenestration for energy conservation and thermal comfort can only be made in clearly defined situations. At the exploratory stage of design it must suffice to recognize certain thermal constraints that may eventually limit the glazed area:

(i) In heated spaces, north facing glazing should have the minimum area compatible with acceptable daylighting or view.

(ii) The net seasonal heat loss through south facing glazing is not so sensitive to changes in glazed area and there is less constraint on size, although the night-time peak heat loss will be the same as for north facing glazing and solar gain in summer could be excessive without shading, causing thermal discomfort and, in air conditioned spaces, increased energy demand.

B.3.2 STEP 2: Rooflight and window sizing

It is important to consider the primary function to be served by each window or rooflight in a building, because the criteria differ [BS8206, Part 2, Clause 3]. Having considered broadly the requirement for daylight and the potential constraints, the next stage is to establish the appropriate average daylight factor targets and to find the amount of glazing required.

The designer should consider the potential of rooflighting first; where illuminance over the working place is the primary concern (and the area is large) this form of lighting is generally the most effective provided that the admission of direct sunlight and excessive solar gain can be controlled, and provided that the glazing can be cleaned easily. Side windows may enhance the appearance of objects within the room more effectively than rooflights.

(1) Rooflight

If rooflighting is accepted the type of rooflight and the area of glazing necessary should be determined by the sequence described below:

(1.a) Choose rooflighting profiles

Figure B.7 illustrates different rooflight profiles. For flat or low-pitched roofs consider barrel rooflights or horizontal rooflights. For wider spans consider shed rooflights. All above provide a high daylight factor for a given area of glazing, but invite solar gain problems in summer.

Where solar gain would be disadvantageous, consider sloping sawtooth or vertical sawtooth; these must face away from the equator. Directional lighting may restrict layout of machinery.

Where sawtooth profile is unacceptable, consider monitor rooflights, such as vertical symmetrical monitors, sloping symmetrical monitors or asymmetrical monitors.

Table B.5 summarises the characteristics of various rooflight profiles. The flow chart shown in Figure B.8 describes the procedure for choosing an appropriate rooflight profile.

(1.b) Choose glazing material

When glazing material is chosen, consider:

- maintenance characteristics (effects of weathering, etc.)
- light transmittance
- thermal transmittance (U-value)
- solar gain factor/shading coefficient
- safety: glazing may need wired glass or equivalent
- colour effects.

(1.c) Estimate glazed area

Glazed area interacts with choice of glazing material:

(i) For a given daylight factor the glass area is inversely proportional to luminous transmittance;

(ii) For a given rate of heat loss through the glazing the glass area is inversely proportional to the U-value;

(iii) For a given daily mean rate of solar gain through the glazing, the glass area is inversely proportional to the solar gain factor.

The Outline of the procedure to follow is:

(i) Specify target average daylight factor;

(ii) Estimate glazed area to provide target average daylight factor;

(iii) Check winter energy balance;

(iv) Check solar gains;

(v) Reconcile thermal consideration with daylight demands, if necessary by manipulating the area or other physical parameters of the rooflights.

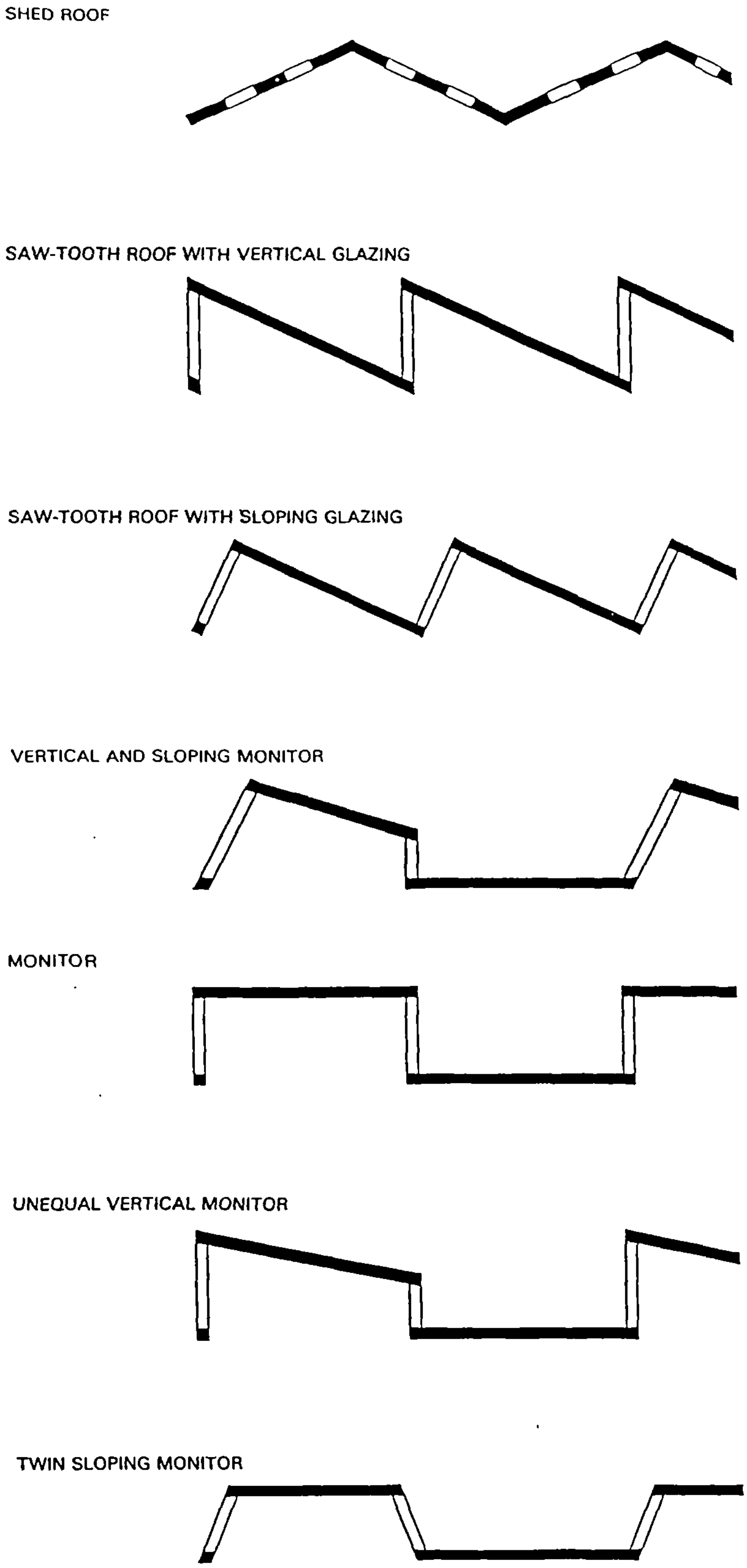


Figure B.7 Rooflight profiles (from Figure A2.2 of CIBSE Application Manual *Window Design*, pp.10)

Table B.5 Characteristics of various rooflights
(Reproduced from the hand-out of the Mid-Career College Seminar '*Harnessing Daylight*', April 1993)

	Sunlight penetration	Heat loss	Obstruction by overhead services etc.	Effect of dirt	First cost	Other factors
Horizontal domes	Very serious	Low	Low	Bad	Medium	
Shed	Very serious	Low, but not enclosed volume	Moderate	Bad	Low	
Sawtooth	Orientation is critical	Main loss through glazing	Can be serious	Moderate	Medium	Note directional effects
Monitors	Can be controlled by careful design	High loss through glazing	Can be kept low by careful design	Can be kept low by careful design	Can be high	Daylight factor usually inadequate
Windowless	Nil	Minimal	Not applicable	Control simplified	Low	Artificial lighting most expensive

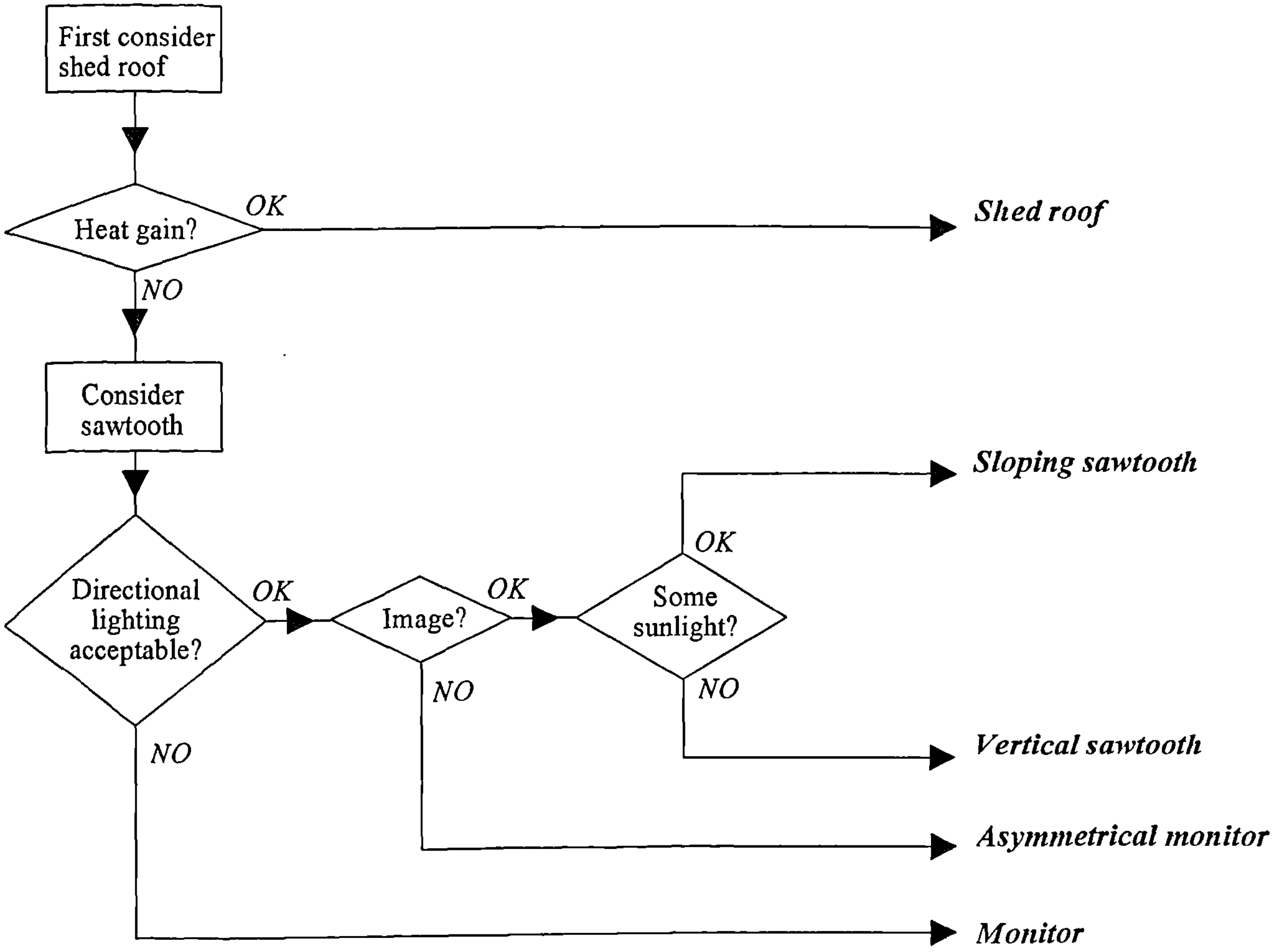


Figure B.8 A flowchart for selecting a suitable rooflight type
(Reproduced from the hand-out of the Mid-Career College Seminor, '*Harnessing Daylight*', April 1993)

(1.d) Establish rooflight position

If rooflight spacing/height ratio are excessive the illumination will look patchy. The distance between any wall and the nearest rooflight should not exceed half the distance between adjacent rooflights, unless the wall contains windows of a reasonable size. The spacing/height ratio thus determines the minimum number or maximum spacing of rooflight runs. Also consider:

- feasible structural spans
- access to rooflights, for cleaning indoor and outdoor surface,
- possible obstructive effects of overhead cranes and piped and ducted services.

(1.e) Establish window dimensions

Having established the rooflight profile, the overall area of glazing required and the number of rooflight, establish the glazed area of each rooflight and hence their individual dimensions.

(2) Side windows

It is not always feasible to optimise window design separately for each individual room in a particular building. Designers should therefore identify, on each principal facade, one or two key spaces.

(2.a) Specify window glazing material

When glazing material is chosen, consider:

- luminous transmittance
- thermal transmittance (U-value)
- solar gain factor
- acoustic attenuation
- desire for privacy which may imply the permanent use of curtains or non-transparent glazing
- colour of glass.

(2.b) Check depth of room

If an interior is too deep, in relation to the height of the window head above the floor, it cannot satisfactorily daylit. Carry out the depth check in terms of:

(i) no-sky line, and

(ii) Limiting depth (windows on one wall only),

both of which are explained in the Appendix B.2.

(2.c) Estimate area of window glazing required

Glazed area interacts with choice of glazing material:

(i) For a given daylight factor the glass area will be inversely proportional to luminous transmittance;

(ii) For a given rate of heat loss through the window the glass area will be inversely proportional to the U-value;

(iii) For a given daily mean rate of solar gain through the window, the glass area will be inversely proportional to the solar gain factor;

(iv) For a given level of intrusive noise from outdoors, there is an inverse relationship between the window area and its transmission coefficient.

The sizing procedure is as follows:

(i) Specify target average daylight factor

When average daylight factor is 5 % or more, an interior will look cheerfully daylit. When the average daylight factor is less than 2 %, the interior will not be perceived as well daylit, and electric lighting may be in constant use. To estimate average daylight factor the following expression can be used:

$$\overline{\mathrm{DF}} = \frac{TW\theta}{A(1-R^2)} \qquad \textbf{(B.2)}$$

where T is the diffuse transmittance of glazing material including effects of dirt, W is the net glazed area of window (m^2) (typically metal window frames are 20 % of total area and timber and plastic frames are 30 % of the total area), A is the total area of interior surface (ceiling and floor and walls, including windows), and θ is the angle in degrees subtended, in vertical plane normal to the window, by sky visible from the centre of the window (see Figure B.6).

(ii) Estimate window area to provide target daylight factor

Glazed area will depend mainly on:

- luminous transmittance of glazing material;
- extent of outdoor obstructions
- size and shape of interior
- reflectance of interior surfaces.

The window area, W, for a given average daylight factor is estimated by inverting Equation B.2:

$$W = \frac{\overline{\mathrm{DF}}\, A(1-R^2)}{T\theta} \tag{B.3}$$

where T is the diffuse transmittance of glazing material including effects of dirt, W is the net glazed area of window (m^2), A is the total area of interior (m^2), R is the area-weighted average reflectance, and θ is the angle in degrees subtended, in the vertical plane normal to the window, by sky visible from the centre of the window. For detailed explanation, see the CIBSE Application Manual "*Window Design*", Part B [1987].

(iii) Check winter heat loss

Consider fabric loss through windows and potentially beneficial solar gain through windows. Fabric heat loss is proportional to U-value which depends on:

- exposure (sheltered, normal or severe)
- framing material
- air spaces in double or triple glazing
- surface coating or gas filling for multiple glazing.

Potentially beneficial solar gain depends on:

- solar gain factor, which depends on choice of glazing
- orientation of window
- outdoor obstructions to winter sunlight.

(iv) Check summer energy balance

The daily mean rate of solar gain under heatwave conditions is proportional to window area, daily mean solar irradiance and solar gain factor. Daily mean solar irradiance at a given location depends on:

- orientation of window
- outdoor obstructions.

Solar gain factor depends on

- choice of glazing material
- choice of solar protection.

Choose adequate solar protection measures, e.g. use of surface or body tinted glass, internal or external shading system such as screen, horizontal or vertical.

(v) Check noise transmission

Site appraisal should have indicated any likelihood of disturbance from traffic, aircraft, railways etc. External noise penetration may be reduced by one or more of the following expedients, depending on the type of noise source:

(a) use of fixed windows

(b) design acoustic barriers

(c) use acoustic double windows (windows with wide internal air space)

(d) use thick glass

(e) reduce window area.

(vi) Complete sizing procedure

Reconcile thermal constraints and acoustic constraints with daylighting requirements, if necessary by manipulating the area or other physical parameters of the window.

(2.d) View consideration

In the case where a priority is given to view, the following guidance can apply to decide glazed areas. The most limited views occur in a deep room when windows are confined to one wall only. Table B.6 gives guidance on minimum window area for a satisfactory view when fenestration is restricted to one wall: higher proportions are recommended. The table gives total window area of the room as a percentage of the internal window wall area. When there are windows in two or more walls, the total area of glazing should not be less than the area restricted to any one wall. The openings should be distributed to give views from all occupied area of the room.

Table B.6 Minimum glazed areas for view when windows are restricted to one wall [BS8206, Part 2, p.8]

Depth of room from outside wall (m)	Percentage of window wall as seen from inside (%)
⟨ 8	20
8 - 11	25
11 - 14	30
⟩ 14	35
NOTE:	Windows which are primarily designed for view may not provide adequate task illumination.

B.3.3 STEP 3: Window shape and position

Having established the area of glazing for side windows necessary for the required average daylight factor within the interior, the next step is the arrangement of this glazing to achieve not only an acceptable distribution of daylight but also to satisfy other requirements such as view, privacy and freedom from glare.

Placing windows in more than one wall, where feasible, has potential advantages:

(a) They promote cross ventilation in naturally ventilated rooms, doubling or trebling the ventilation under heatwave conditions.

(b) They relieve dense shadows and harsh contrasts in side-lit rooms.

(c) They reduce the risk of sky glare by increasing window wall illuminance. It should be borne in mind, however, that the risk of overheating may be increased.

To determine the shape and position of windows, the following aspects should be considered.

(3.a) Daylight distribution

The average daylight factor should have been settled in (2.c) (i) and (ii). The following procedure will optimise the window shape and position for interior lighting:

(i) Identify work stations or critical points at which good natural lighting should be ensured. If at this stage no such points are apparent select points remote from the window.

(ii) Arrange the shape and position of windows in relation to outdoor obstructions so that the largest possible area of sky is visible from these critical points.

(iii) If necessary calculate the daylight factor at critical points.

(3.b) Glare

Three sources of window glare can be distinguished: direct sunlight, reflected sunlight and skylight. Most complaints are due to direct sunlight.

(i) Direct sunlight

A direct view of the sun within 45° of the principal viewing direction will be intolerably glaring. This must be avoided; if necessary use blinds or curtains. Not that protection from direct solar radiation also gives visual protection from sunlight. The best strategy for solar protection from sunlight is therefore to concentrate on solving the thermal problem.

(ii) Reflected sunlight

Glare may be experienced from light-coloured, highly reflective sunlit surfaces viewed from the interior of a deep office. The simplest remedy would be an interior curtain or blind.

(ii) Skylight

If the window faces an unobstructed horizon and no ground is visible to observers inside the room, glare discomfort will be virtually independent of window shape or size, and will depend mainly on the luminance of sky seen through the window. Any view of external obstructions will 'buffer' sky glare. If this is an important consideration in design, plan window shape and position so that observers see relatively more obstructions than sky. Splayed reveals, windows in more than one wall, low-transmission glass and high-reflectance walls all reduce sky glare by diminishing the brightness difference between the window and the wall in which it is set.

(3.c) View

The outside view often comprises three strata: sky, buildings and foreground. Information is especially contained in transitions between layers. In planning the position of windows, the following factors are important [BS8206, Part 2, Clause 4.2]:

(i) Most people prefer a view of a natural scene: trees, grass, plants and open space;

(ii) A specific close view may be essential, particularly for security and supervision of the space around dwellings;

(iii) There is often a need for privacy. This varies with the building type and with the expectations of the users. The view into a building should be considered when the view outwards is determined.

The size and proportion of windows should depend on the type of view, the size of the internal space, and the position and mobility of occupants. Unless a view of sky is to be deliberately excluded (and the penetration of daylight severely limited) window heads should be above standing eye height. Sills, normally, should be below the eye level of people seated. Transoms should not obstruct significant parts of the view from normal standing or sitting positions [BS8206, Part 2, Clause 4.4].

(3.d) Privacy

Three channels for visual intrusion may affect the position of windows: from interior to exterior, from exterior to interior, and from interior to another interior.

(3.e) Finalise shape and position of window

In general one can expect a conflict between the demands of:

- daylight (requiring maximum vie of high-altitude sky);
- glare (requiring excessive contrast to be reduced);
- view (requiring access to skyline but little additional sky. Also access to foreground).

Reconcile these demands, preferably without returning to the previous Step 2 to modify window area.

B.4 Energy consideration in artificial lighting

Lighting design should be carefully carried out so that desired lighting conditions are provided at minimum energy cost. It should also be borne in mind that an installation can be expensive in terms of first cost and running costs. There are two factors which control the energy consumption of an artificial lighting installation, i.e. the power required to provide the lighting and the time for which that power is used. The former is determined by the designer, the latter is determined by the user within the limits set by the designer [BS8206, Part 1, Clause 6].

B.4.1 Power

The power required to provide the designed lighting conditions is influenced by

(1) the type of lighting system used
(2) the choice of light source, and
(3) the choice of luminaire.

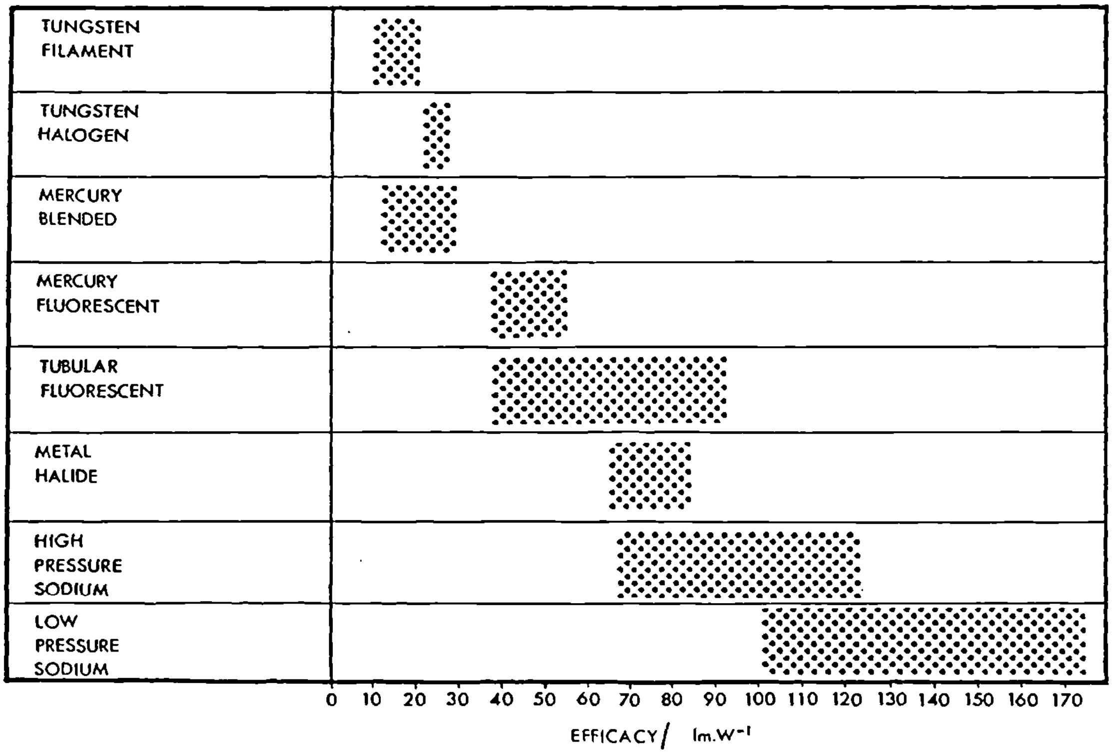
(1) The type of lighting system used

The most common form is *general lighting* in which the same illuminance is provided over a large area. Two other forms are *localized lighting*, which is used when a large area can be conveniently split into a number of smaller areas requiring different lighting conditions, and *local lighting*, where there may be two lighting installations: one providing general lighting as a background and another providing local lighting on the task. As a general rule, the installation load for local lighting is less than for localized lighting, which in turn is less than for general lighting. The choice between these different lighting systems, however, is not simply a matter of installed power. Rather, it is governed by organizational, technical and financial factors which determine the suitability of local and localized lighting to particular circumstances [BS8206, Part 1, Clause 6].

(2) The choice of light source

Different light sources convert electricity to light with different efficiencies. This efficiency is called *luminous efficacy* (lumens per watt). Table 2.7 gives a comparison of the ranges of luminous efficacies of the different lamp types. But, it should be noted that the discharge light sources, including fluorescent lamps, require a control circuit which increases the power requirements. For any specific application, the light source with the highest luminous efficacy and which is consistent with the other requirements of the application should be chosen [BS8206, Part 1, Clause 6].

Table B.7 Comparison of luminous efficacies (from Table 3.3 of the CIBSE *Code for Interior Lighting*)



(3) The choice of luminaire

For the purpose of minimizing installed power, the only important characteristic regarding luminaires is *utilization factor*. This is the total proportion of the lamp light output which reaches the working plane. This is not a unique property of the luminaire itself, as it is also governed by the room in which the luminaire is placed. A luminaire in a large room with high surface reflectances, will generally have a higher utilization factor than when placed in a small room with low surface reflectances. Provided it complies with the other requirements, the luminaire with the highest utilization factor for the interior under consideration should be selected [BS8206, Part 1, Clause 6].

B.4.2 Time: Control methods

The other aspect of minimizing energy consumption is controlling the hours of use of the installation. The lighting system must be designed and managed to permit good control of energy use. The importance of lighting control should not be underestimated. In a conventionally daylit commercial building the choice of control can make 30 % to 40 % difference of the resulting lighting use [BS8206, Part 2, Clause 9.4].

Lighting controls should be arranged so that the lighting load can be reduced in parts of buildings when no one, or perhaps very few people are in occupation, and also at times when daylight is providing a high illuminance over at least some of the working area [BRE Digest 272, 1983]. They can take many forms, varying from a simple wall switch to being a part of a sophisticated microprocessor-controlled building management system. But the methods of control can fall into three broad categories: (a) Manual control; (b) Automatic control; and (c) Processor control [CIBSE *Code for Interior Lighting*, 1984].

(a) Manual control

Manual methods rely upon individuals and appointed members of staff controlling the lighting system. These methods tends to be inexpensive in capital costs but may be less effective than automatic methods. To be effective the lighting system must be well planned to permit flexible switching of individual luminaires or banks of luminaires: where there is more than one luminaire, the controls should permit individual luminaires or rows of luminaires parallel to window walls to be controlled separately; each switch should preferably control a small group of luminaires so that they are switched by the occupants most affected; switches should be as near as possible to the luminaires which they control. An education programme to ensure staff awareness is essential.

(b) Automatic control

Automatic control systems, such as time switches, photocells or occupation sensors, can be inexpensive and can switch (or dim) banks of lights. They must normally have some degree of manual override (on and off) to cater for unexpected circumstances.

Time switches provide a convenient method of ensuring that unwanted lighting is not provided outside working hours. Arrangements should be made for individuals working late or over the lunch time, to override a part or all of the switching with subsequent automatic switching-off.

Photocells can monitor the level of useful daylight and turn off, or dim, luminaires or individual lamps in rows near the windows. Usually this kind of control can only economic, in relation to the capital cost, in large buildings with large daylit areas which are continually occupied during the day, e.g. offices, factories, schools and public circulation areas. Whether or not this is economic will depend upon the daylight factor and the proportion of the working year for which the required illuminance is exceeded.

Occupation sensors can be used to detect the presence of occupants and to ensure that the lighting in a room is switched off when it is empty. A time-lag must normally be built into the system to prevent premature switch-offs. Their cost may militate against their use in small spaces.

(c) Microprocessor-based control

Microprocessor-based, or computer-based, control systems rely upon dedicated processors, or computers, to control some or all of the building services, not only lighting but also other building services, such as air-conditioning, lifts, fire alarms. One of the most important advantages of such an approach is that complex decisions can be made from moment to moment, based upon the precise state of the building's operation. Another significant benefit is that the system is controlled by software, i.e. the control programs can be refined and tailored to suit the building and can be easily amended to suit changed circumstances. Such intelligent systems can continuously monitor the building to operate it at maximum efficiency and economy [CIBSE *Code for Interior Lighting*, 1984].

B.5 Lighting Design Process

Lighting design is a complex process and no hard and fast rules can be derived which will suit all design problems or every designers. The CIBSE *Code for Interior Lighting* [1984], nevertheless, presents a design approach for artificial lighting design practice which gives a guidance to less-experienced designers [CIBSE *Code for Interior Lighting*, Part 4]. It comprises 5 stages, as illustrated by a flow chart in Figure B.9, namely:

A. Objectives

Determine the objectives of the design in terms of the safety requirements, the task requirements and the appearance required. Priorities should be allocated to the design objectives and constraints identified;

B. Specification

Express the design objectives as a set of compatible design criteria, and acknowledge those objectives which cannot be quantified;

C. General planning

Consider the relationship between natural and artificial lighting. Resolve the type of lighting system which will achieve the desired objectives. If it proves difficult to plan an installation which meets the design specification, it may be necessary to reassess the original objectives;

D. Detailed Planning

Plan the final scheme (or alternative scheme) using accurate data to ensure the most economical and efficient final design;

E. Appraisal

After completion, examine the installation in order to assess its success in terms of the design objectives and its acceptability to the client or users.

Since the scope of this study is limited within the early, 'strategic' phase of the building design process, detailed explanation relating the first three stages, extracted from the CIBSE *Code for Interior Lighting*, Part 4, is given below.

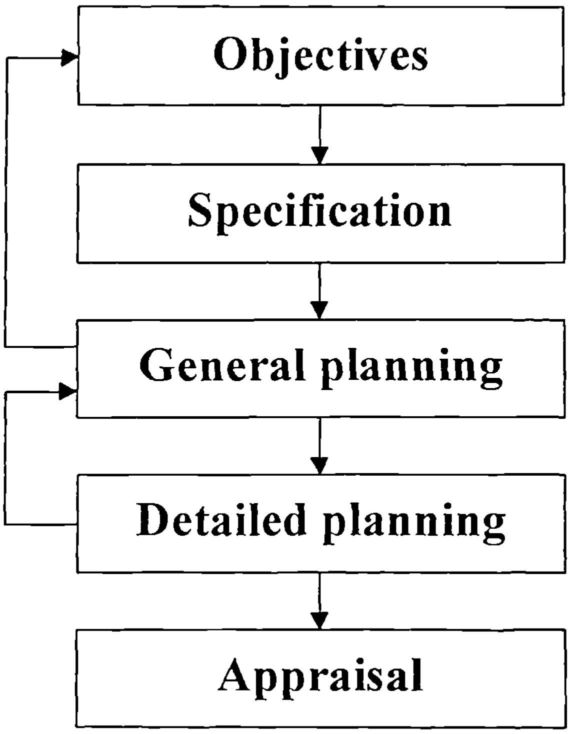


Figure B.9 Lighting design flow chart [CIBSE *Code for Interior Lighting*]

A. Objectives

The first stage in planning any lighting installation is to establish the *lighting design objectives*. Establishing them is a matter of deciding what the lighting is for. Care and time expanded on this should be well invested, because the objectives will guide the decisions in all the other stages of the design process. The lighting objectives can be considered in three parts:

(a) Safety

The lighting must be safe in itself and must allow the occupants to work and move about safely;

(b) Visual tasks

An analysis of the visual tasks in terms of size, contrast, duration, need for colour discrimination and so on, is essential to establish the quantity and quality of the lighting required to achieve satisfactory visual conditions;

(c) Appearance and character

It is necessary to establish what mood or atmosphere is to be created.

When establishing the objectives, it is important to differentiate between those which are essential and those which are desirable. It is also important at this stage to establish the design constraints. Often the most obvious and the most important constraint is *financial.* Usually, it is possible to relate capital and running costs to establish the lowest overall investment. There are many other constraints which may affect the design objectives, such as *energy consumption*, *environmental considerations*, *physical problems of access.* These constraints must be recognized at the objectives stage of the design [CIBSE *Code for Interior Lighting*, Part 4, p.88-89].

B. Specification

Once the lighting objectives have been defined, they must be expressed in a suitable form. Not all design objectives can be expressed as measurable quantities [CIBSE *Code for Interior Lighting*, p.89].

Lighting designers have a responsibility to ensure that lighting is not liable to cause injury to the health of occupants. Therefore, the designer must always take due note of statutory instruments that affect lighting conditions, such as *Health and Safety at Work etc. Act* 1974, *Factories Act* 1961. Most of these demand that lighting shall be both sufficient and suitable. 'Sufficiency' is normally taken to be related to the quantity of illumination (illuminance) on the tasks and for safe movement, whilst 'suitability' covers discomfort and disability glare, spectral distributions, veiling reflections, shadows, and so on [CIBSE *Code for Interior Lighting*, Part 4, p.90].

A full specification can be established by reference to the CIBSE *Code for Interior Lighting* and by taking the design objectives into account. The factors which can be specified numerically are: *financial budget*, *energy budget*, *design service illuminance*, *uniformity*, *modelling*, *vector/scalar ratio*, *illuminance ratios*, *reflectance and colours of interior surface*, *light source colour* (CCT: correlate colour temperature), *colour rendering requirement*, *glare*, *run-up/re-strike time* [CIBSE *Code for Interior Lighting*, Part 4, p.80-90].

C. General planning

When the design specification has been established, the purpose of the remaining stages of design is to translate these physical requirements into the best possible solutions, with the intention of meeting the original objectives. The planning stages can be divided into *general planning* and *detailed planning*. At the general planning stage, the designer aims to establish whether the objectives are viable, and resolve what type of design can be employed to satisfy these objectives. The first stage in the general planning of lighting installation is to consider the interior to be lit, its proportions, its contents, and most importantly the daylight available.

(1) The relation between natural and artificial lighting

Window design affects not only daylighting but also other environmental factors, such as solar gain in summer, fabric heat loss in winter, natural ventilation, the entry of noise and dirt from outside, the view in and out, the composition of the architectural facade. The questions to be considered are: how should the artificial lighting relate to the natural lighting; and does the window or rooflight need additional visual or thermal protection. The window design issues were explained, based on the CIBSE Application Manual *Window Design* [1987], in Appendix B.3 of this thesis.

Since the daylighting may well suggest the form and especially the control system of the artificial lighting. In relation to the daylight availability, four distinct conditions of the types of interior are considered [CIBSE Application Manual *Window Design*, 1987, p.21]:

(a) Average daylight factor exceeds 5 %

Natural lighting level should be adequate for most purposes during normal daylight hours. Plan electric lighting primarily for night-time use.

(b) Roof-lit interiors with average daylight factor below 2 %

Supplementary electric lighting will be needed almost permanently. If automatic controls are adopted they may be designed to switch different luminaires at fixed steps of illuminance, or to dim them.

(c) Average daylight factor between 2 % and 5%

Electric lighting should be planned to take full advantage of available daylight. Savings from automatic controls are particularly rewarding. Using daylight to provide ambient background lighting, localized lighting may be advantageous.

(d) Deep side-lit rooms

Electric lighting should be carefully zoned, switching-zones near windows being defined partly by daylight factor contours. Lamps with '*intermediate*' correlate colour temperature are generally recommended.

(2) Choice of lighting systems

(a) General lighting

General lighting systems provide an approximately uniform illuminance over the whole working plane. Luminaires are normally arranged in a regular layout. The greatest advantage of such systems is that they permit complete flexibility of task location. The major disadvantage of general lighting systems is, however, that energy may be wasted illuminating the whole area at the level needed for the most critical tasks. Energy could be saved by providing the necessary illuminance over only the task areas and using a lower ambient level for circulation and other non-critical tasks. See also 'local lighting', below.

(b) Localized lighting

Localized lighting systems employ an arrangement of luminaires designed to provide the required service illuminance on work areas together with a lower illuminance for the other area. The illuminance on the other area should not be less than one-third of the illuminance on the work areas. They normally consume less energy than general lighting systems unless a high proportion of the area is occupied by work stations. Considerable care must be taken to co-ordinate the lighting layout to task positions and orientation. The system can be inflexible, and therefore correct information is essential at the design stage.

(c) Local lighting

Local lighting provides illumination only over the small area occupied by the task and its immediate surroundings. It is generally provided by luminaires mounted on the work station, e.g. desk lights. Local lighting can be a very efficient method for providing adequate task illumination, particularly where high illuminances are necessary and/or flexible directional lighting is required. A general lighting system must be installed to provide sufficient ambient illumination for circulation and non-critical tasks. The general surround illuminance should not be less than one-third of the task illuminance [CIBSE *Code for Interior Lighting,* p.93-95].

(3) Choice of lamp and luminaire

The choice of lamp will affect the range of luminaires available, and vice-versa. One methods of design is to follow a procedure which does not try to identify a single lamp and luminaire combination but rather rejects those combinations which are unsatisfactory. Then, because all of the unrejected luminaire and lamp combinations are acceptable, the most efficient and economically acceptable scheme can be selected [CIBSE *Code for Interior Lighting*, p.95-98].

(a) <u>Choice of lamp</u>

The designer should compile a list of suitable lamps, by rejecting those which do not satisfy the design objectives. The criteria to consider involve:

- (i) luminous efficacy
- (ii) run-up time
- (iii) colour rendering property
- (iv) apparent colour
- (v) life
- (vi) lumen maintenance characteristic
- (vii) stroboscopic effect.

(b) <u>Choice of luminaires</u>

Factors affecting the choice of luminaire are:

- (i) Safety: luminaires may have to withstand a variety of physical conditions, e.g. vibration, moisture, dust, ambient temperature, vandalism and so on;
- (ii) Light distribution: it should be carefully considered as it influences the distribution of illuminance and the directional effects that will be achieved;
- (iii) Utilization factor (UF): that is a measure of the efficiency with which light from the lamp is used for illuminating the working plane; and
- (iv) Luminaire reliability and life: that will have a direct impact of the economics of the scheme.

(4) Lighting control

The lighting system must be managed to permit good control of energy use. Methods of control are explained, in terms of energy consideration in artificial lighting, in Appendix B.4 of this thesis. With any control system considerable care must be taken to ensure that acceptable lighting conditions are always provided for the occupants. Safety must always be of paramount importance [CIBSE *Code for Interior Lighting*, p.99-100]. A guidance on the choice of a suitable lighting control strategy, in relation to the daylight availability of the interior under consideration and its use pattern, is presented by BRE Digest 272 '*Lighting controls and daylight use*' [1983]. The flow chart describing the sequence of selecting a suitable control strategy is shown in Figure B.10.

(5) Maintenance

Lighting systems must be serviced regularly and this must be allowed for at the design stage. For detailed explanation about the maintenance programme for lighting system, see Appendix 7 of the CIBSE *Code for Interior Lighting*.

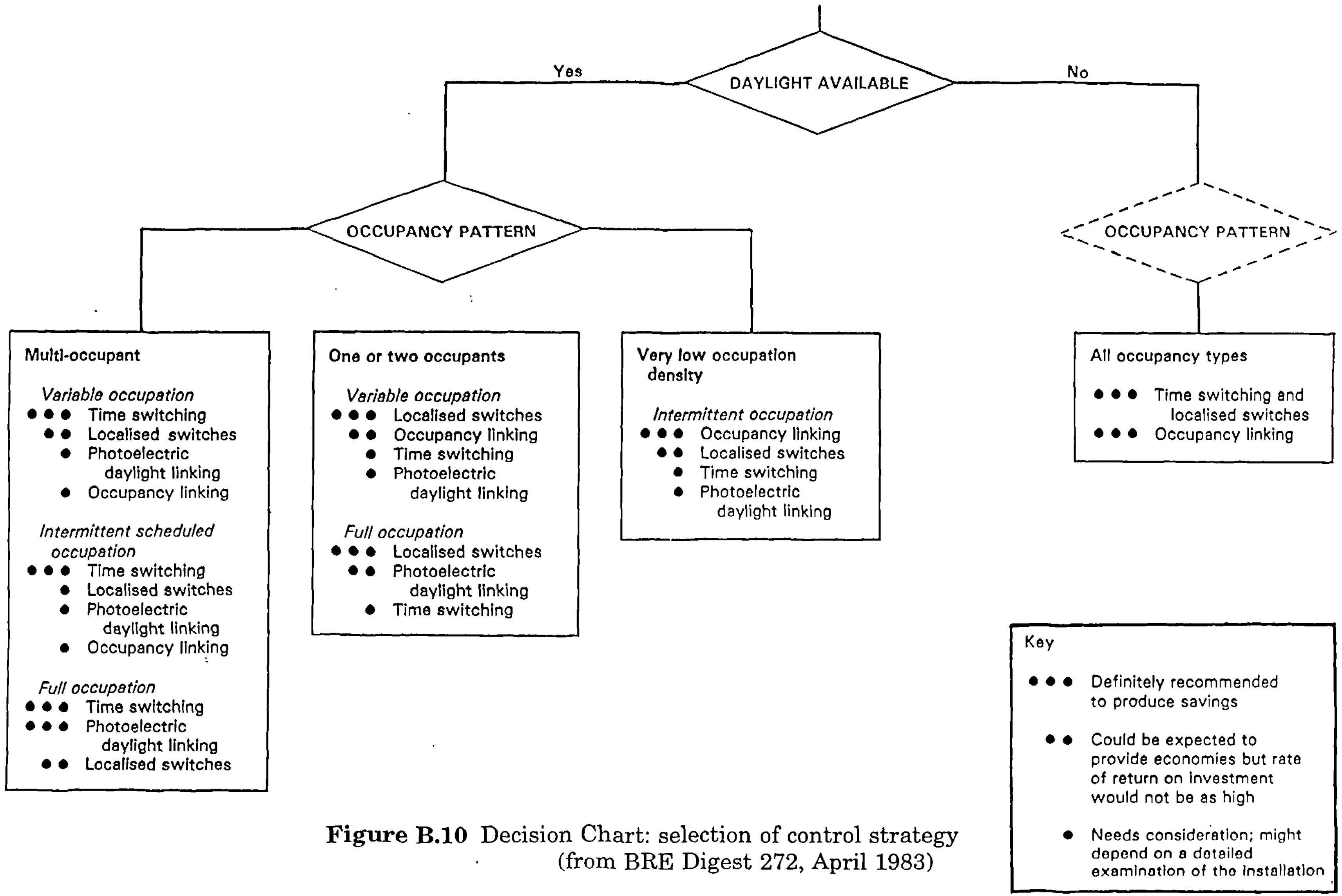


Figure B.10 Decision Chart: selection of control strategy (from BRE Digest 272, April 1983)

Appendix C

Appendix C

CASE STUDY:

Low Energy Design of a New Primary School for St. John's School

C.1 Introduction

A low energy design project was carried out between January and March 1992, as part of the MSc course in *Energy and Built Environment*, at Cranfield Institute of Technology. During the eight week period of the project, one of the four design groups was observed.

The aim of this project was to produce an energy-conscious design for a primary school (Client: the Department of Education and Science, DES), whilst providing a learning opportunity for inter-disciplinary design-working within a group.

There were four groups, consisting of four or five MSc students with different back grounds, such as architects and engineers. The design process was undertaken using many iterative steps allowing ideas to be explored in numerous directions. The method of working was achieved using such tools as *TAS*, a thermal analysis system, the *Daylight Program* for daylighting design, and Philips' *Calculux* for designing artificial lighting installations. British Standard BS8207 was used both to structure the plan of work and as a checklist. The outcome was the development of a workable building model which the group felt complied with the brief.

During the course of the project, there were four critique sessions, held approximately every fortnight, including the final critique where the overall design project was summarised. Appendix C describes how the group developed its design activities in the 3 steps, i.e. (a) the first critique, (b) the second critique, and (c) the third and the final critique. The figures and tables shown in this appendix are extracted from the *Low Energy School Design Project Report, Group 1* (D. Hunt, R. Barton, M. Crisp and I. Dunn, March 1992).

C.2 The First Critique

The group spent the first two weeks mainly analysing the client's brief and establishing its design philosophy and strategy, in accordance with BS8207 Stages 1-5 (see Table 2.2 of Chapter 2, or Table 1 of BS8207).

1. Analysis of the brief

Having received a detailed brief from the client (Department of Education and Science: DES) stressing the significance of energy conservation targets and other aspects of building design including cost, the group set about the task of analysing the brief. (The brief can be found in Design Note 47, by the Architects and Building Branch, DES, 1989.) The analysis included the size of the school required, floor area, user, activities carried out, site, general considerations, energy and lighting considerations, and a schedule of accommodation. Analysis of the brief also required the investigation of possibilities for multiple use of the building (Stage 3 of BS8207).

Not only did the group consider the aim of the project to design an energy efficient building, but it also recognised the following requirements:

(i) creating a family atmosphere;
(ii) providing a safe environment;
(iii) providing disabled access;
(iv) discouraging vandalism;
(v) providing required comfort levels; and
(vi) creating an aesthetically pleasing building.

The group also recognised that the comfort of the occupants within a building must be inherent in every aspect of the building design by virtue of its fundamental role of modifying the ambient environment.

A further guide to the design process laid down by the DES involved compliance with various sections of Design Note 17 "*Guidelines for Environmental Design and Fuel Conservation in Educational Building*", including the main areas of heating, ventilation and lighting. The requirements of the DES with regard to these sections are summarised below:

Heating

- The chosen system should be capable of heating 10 $m^3/person/hour$;
- Minimum temperatures of 18°C - classrooms
  14°C - hall/gym
  15°C - circulation areas.

Ventilation

- In the working areas and hall a minimum of 30 $m^3/person/hour$ is required, with the use of mechanical ventilation in toilets (6 air changes/hour, ACH) if natural ventilation is insufficient.

Lighting

- Daylight should be the main source of light;
- Regard should be paid to conserving energy in lighting;
- Windows to be arranged to give a satisfactory view.

Energy conservation

- Short heat-up period of heating system is required;
- Fuel with lowest present value (according to capital, maintenance, and operating costs) to be chosen;
- Possibility of changing to other fuels in future.

2. Philosophy and strategy

While analysing the client's brief, the group decided as its design philosophy the minimizing of applied energy of the building, and set its design targets, in terms of Energy Design Value (EDV) and Annual Energy Consumption Value (AECV), at 50% of the DES maximum values, which are 152 W/m^2 and 302 kWh/m^2, respectively. In order to do so, the group established its design strategy as follows:

- exploiting daylight and solar energy;
- use of natural ventilation;
- extensive search of the design options on the design tool *TAS*.

3. Creative thinking

To explore the design criteria and to establish a systematic design process, a brainstorming session was undertaken. Having engaged in this activity, the group obtained a list of possible ideas, ranging from the feasible to the imaginative but totally impractical (Table C.1).

Table C.1 Brainstorming Outcome

1. Structure and Form
- Circular/Hemisphere
- Lightweight construction
- Two/Multi storey
- Demountable partitions

2. Active/Passive Solar Design
- Trombe walls/Sun spaces
- Solar collectors
- Swimming pool (heat storage)
- Transmissive building insulants
- Conservatory (heated/unheated)

3. Environmental
- Pond/trees/courtyard
- Climate exclusive/sensitive
- Evaporative cooling
- Recycled building materials
- Greenery, shade
- Glass bricks

4. Applied Services
- Boiler (condensing)
- Fuel (coal)
- Heat recovery
- Roof ventilation
- Fully Air Conditioned
- Heat pump

5. Controls
- Control zones
- Local control (teacher)
- Energy advice to user on control

6. Finishes
- Materials/Colours
- External (vandalism)
- Wall carpets

7. Radical
- Partially/totally submerged
- Living roof
- Variable properties glazing
- Children generate electricity (treadmill)
- Draw bridge and moat

8. Others
- Microclimate considerations
- External storage spaces
- Daylighting/Sun angles
- Maintenance considerations
- Amount of applied energy

To help organize the requirements of the client's brief into a series of workable, internally linked spaces, the group developed a bubble diagram grouping similar tasks and functions which encouraged energy-conscious planning (Figure C.1). Consideration was given to both the spatial and environmental requirements. The final plan reflects the disposition of spaces found in the bubble diagram.

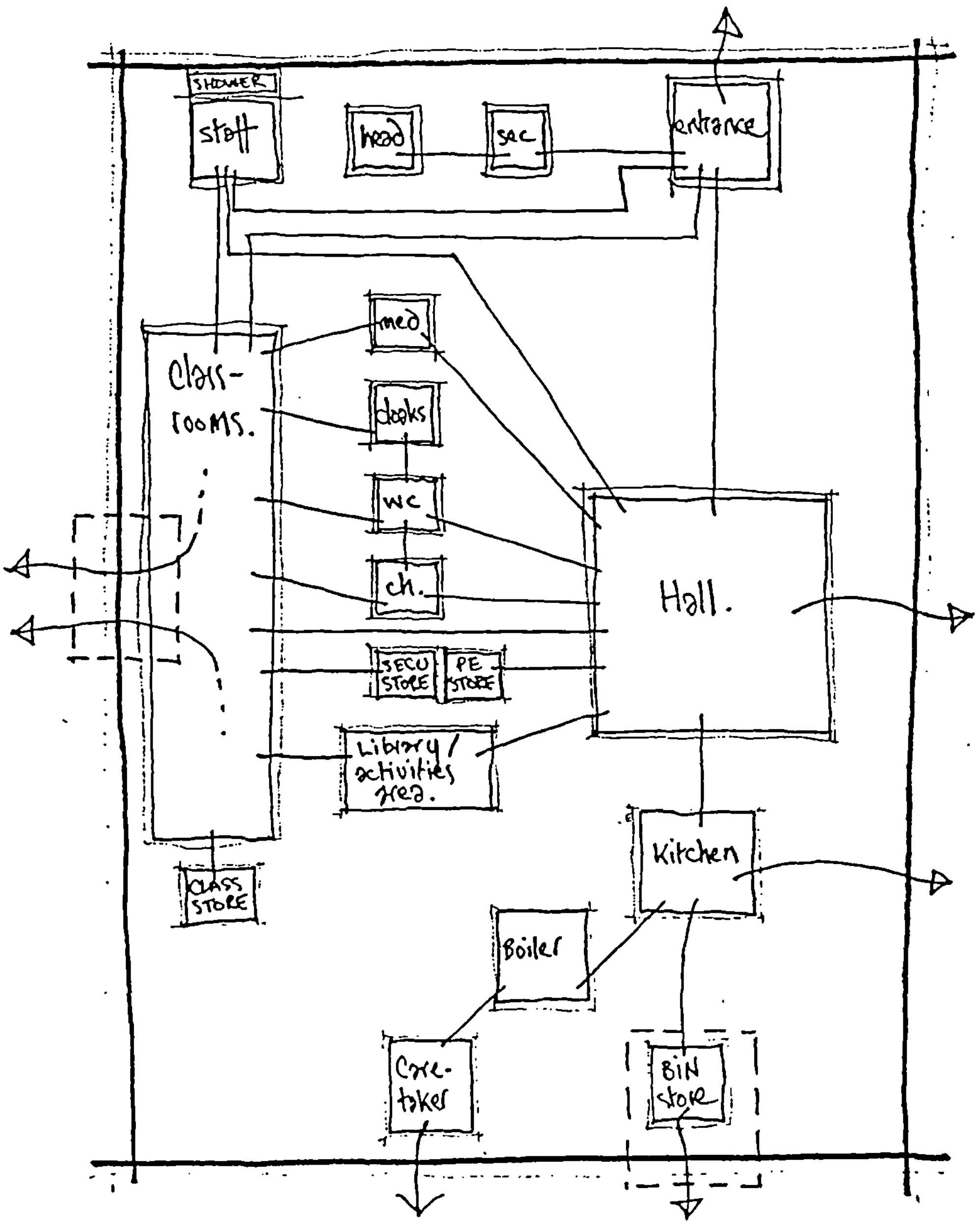


Figure C.1 Bubble diagram showing the connection of spaces

C.3 The Second Critique

The group developed its design concepts while carrying out tests on the computer-based design tools, such as *TAS* and the *Daylight Program*. The group considered and developed its outline design proposals in terms of building form, internal layout, site layout, structure and construction, and daylighting, according to the BS8207 Stages 6-11.

4. **Form** (Part 1)

4.1 Nine-square approach

Not wishing to discount unusual ideas or concepts, the group adopted a systematic approach in the development of the design. The various areas included within the brief were approximated to nine squares, each being 100 m^2, so that a series of designs with equal area could be developed and modelled from this simple "nine-square" model on a comparative basis (Figure C.2). The "nine-square" concept was adopted:

(i) to allow maximum participation by each member of the group in the complex process of designing the school, despite the group's limited design experience;

(ii) to allow maximum use of the *TAS* system; and

(iii) to allow early exploration of building form to be carried out with simple shapes before a more complex design was undertaken.

Figure C.3 shows the "nine-square" family tree which illustrates a summary of the approach, in relation to construction types (Section 4.2 'Test Cell Analysis'), roof shapes (Section 4.4), internal planing (Section 5. 'Internal Layout'), and site layout (Section 6).

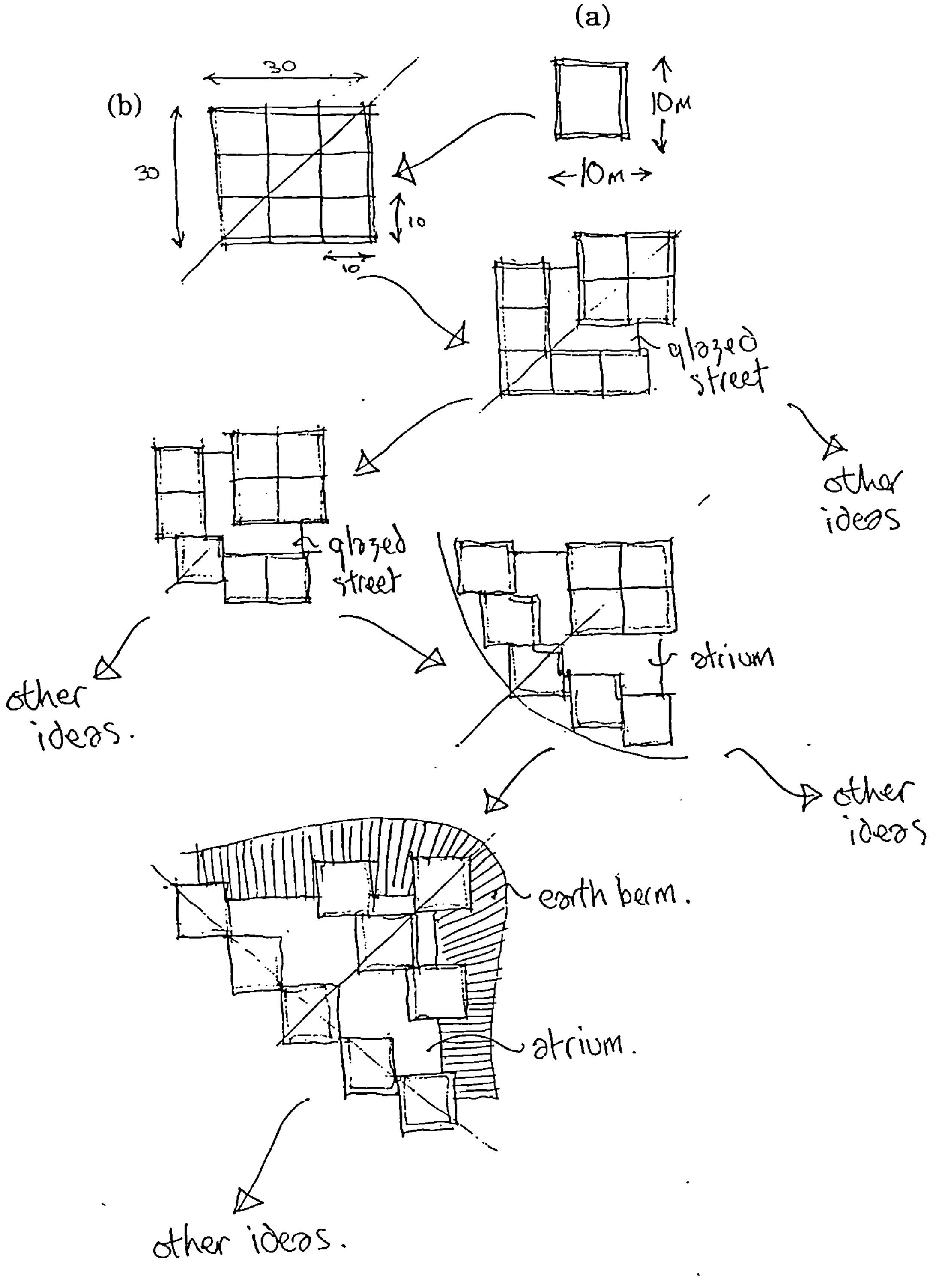


Figure C.2 'Nine-Square' approach and the development of building forms: (a) a single component; (b) 'Nine-square'.

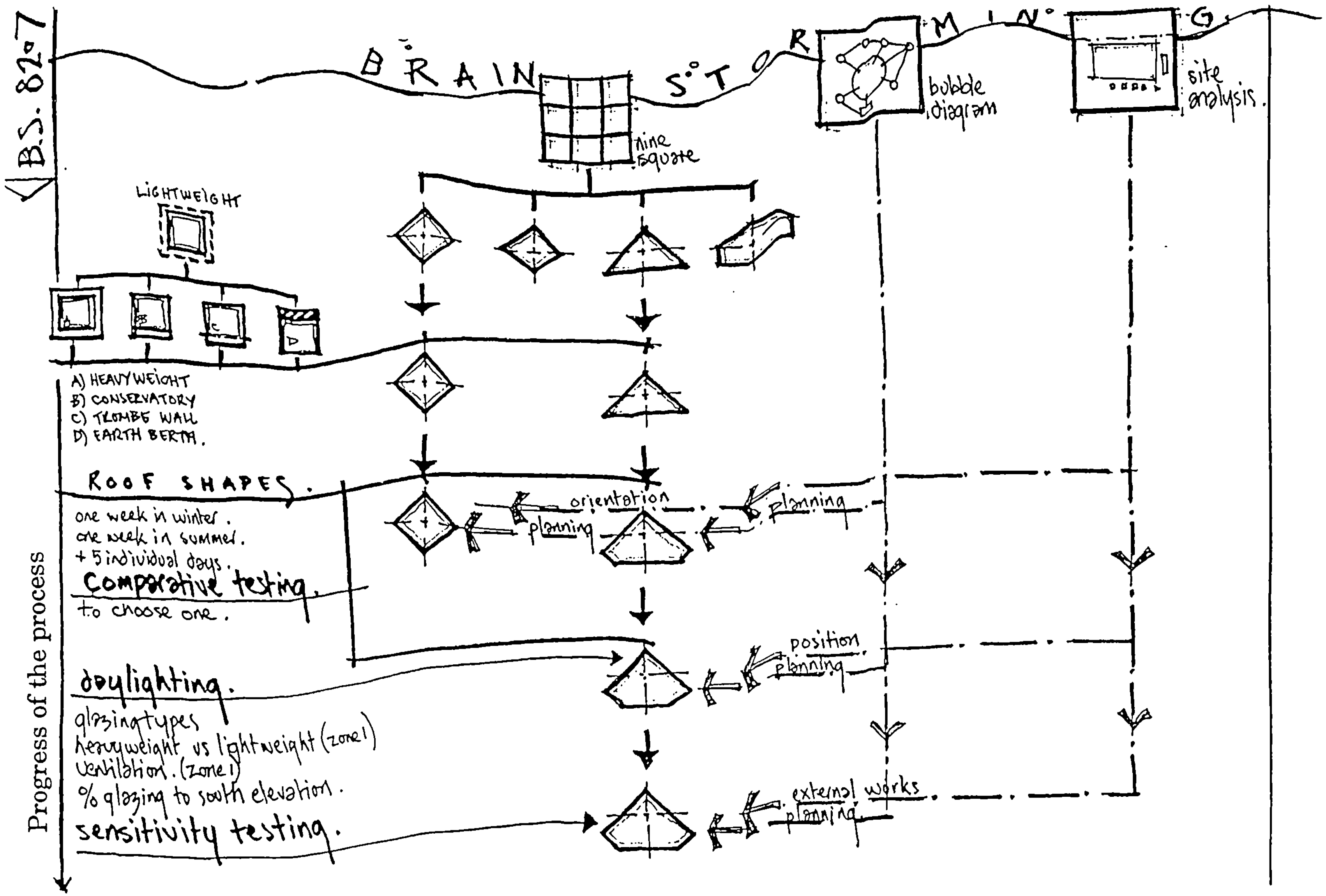


Figure C.3 'Nine-square' family tree

4.2 Test Cell Analysis (form testing and development)

In order to test the relative merits of certain features of construction types, the group carried out a test cell analysis, in which a test module with the following features was tested on *TAS*:

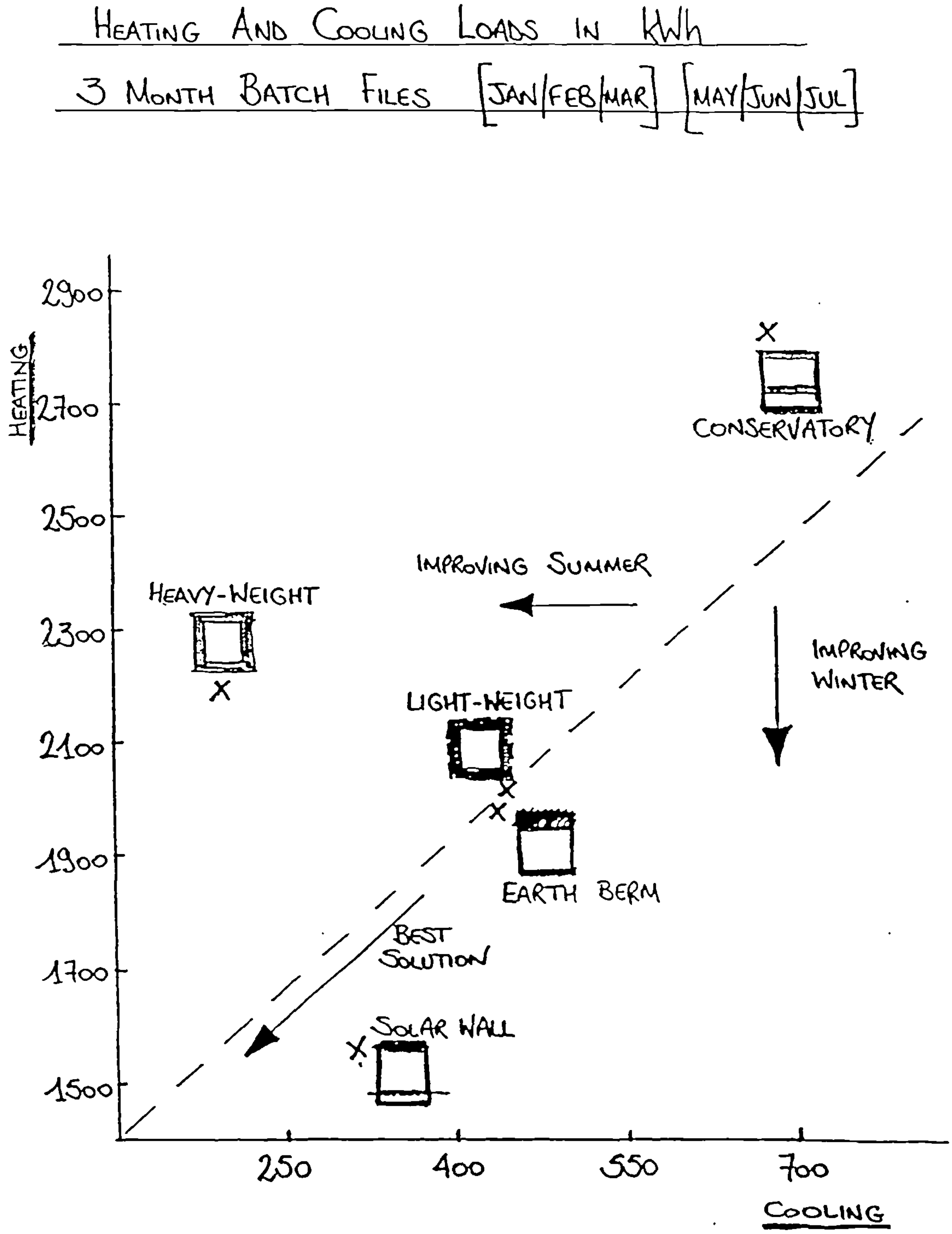
(i) light-weight structure
(ii) heavy-weight structure
(iii) earth berm north wall
(iv) light-weight solar wall
(v) conservatory.

The module was based on the same area with the same conditions, and tested over three months in each of two seasons, i.e. winter and summer. The results of this test are illustrated in Figure C.4. The group concluded that the solar wall had advantages over the light-weight module, but was discounted due to vandalism problems; the conservatory had also to be discounted due to overheating in summer and large heating requirements in winter; the other three options were fairly similar, and led the group to conclude that the choice would be made on other grounds, such as cost and occupancy patterns.

4.3 Early Development

From the results obtained from the test cell analysis and the initial conceptual development of the "9-square" model, a few basic forms were developed, i.e. 'SQUARE', 'TRIANGLE', 'DIAMOND', and 'PENTAGON' (see Figure C.5). These basic forms were modelled upon *TAS* for consideration of aspect ratio and orientation, with identical floor area, glazing area, construction type and internal conditions (the specification is shown Table C.2).

(i) Aspect ratio: Only the shapes with a high aspect ratio demonstrated high winter energy requirements (Figure C.5).
(ii) Orientation: See Section 6.2 'Orientation'.



HEATING AND COOLING LOADS IN KWh

3 MONTH BATCH FILES [JAN/FEB/MAR] [MAY/JUN/JUL]

Figure C.4 Test cell analysis

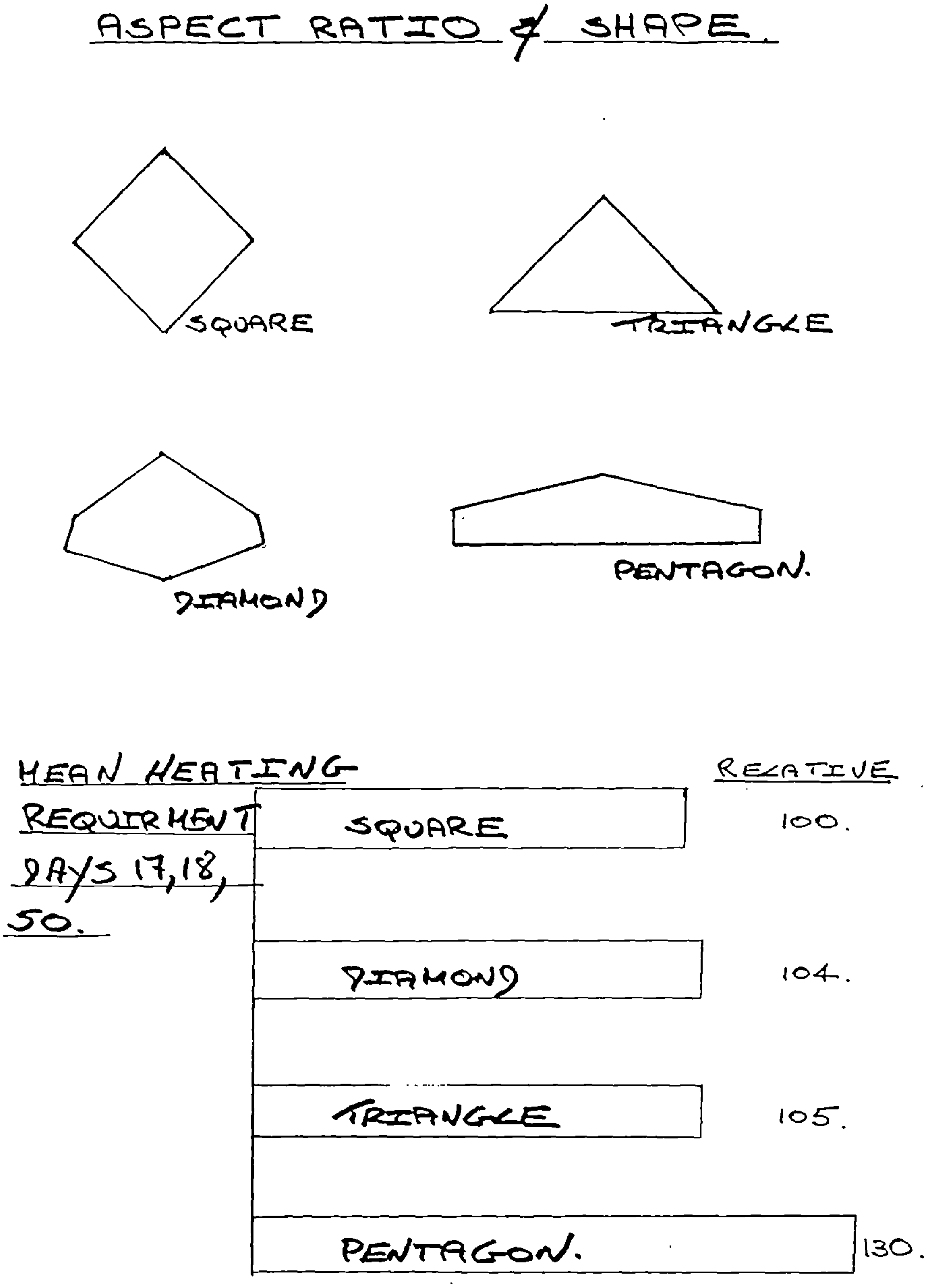


Figure C.5 Early development of building forms:
four shapes and their relative heating requirement

Table C.2 Test Specification

Floor:	Concrete Slab		
External wall:	Lightweight single brick skin		
Roof:	Flat Asphalt		
Glazing:	Southern Aspect	-	ref. Square 40%
	Other Aspects	-	ref. Square 10%
Rooflight:	Double Glazing		
Zones:	2		
Internal condition:	Occupied 8.00 - 16.00 hours.		
	Lights, Sensible and Latent Gains		
	Ventilation (24hours) 0.5 air change per hour		

5. Internal layout

Bubble diagram

The schedule of accommodation was organized schematically into a bubble diagram to allow the group to establish the association of complementary uses and the connection of spaces (see Figure C.1).

Classrooms: On the basis of providing useful solar gain and views out across the recreational areas, the group decided that a southern aspect was best given to the classrooms. Pairs of class bases were spatially linked to the common teaching and circulation areas, the rear and the quiet areas, and to the front of classrooms.

Library and Activity room: Linked to the class area.

Hall: Linked to the class area.

WCs and Changing areas: Throughout the building

Entrance and Reception: Staff room, medical room, head teacher's and secretary's room, and access route to the hall and class area were grouped around.

Kitchen: Linked to the hall.

Access: Full access to all the facilities, including WCs, with no steps, and an enlarged parking space were considered for the disabled. After hours access was also considered.

6. Site layout

Having studied the site conditions, the group decided that the existing site boundary fencing and walls would be retained with the option of upgrading following further cost discussions with the client. The plan of the site is shown in Figure C.6. The factors which influenced the site layout included 'overshadowing' and 'orientation', simulated on *TAS*.

6.1 *TAS* shadow simulations

The group studied the effect of the shadows created by the building being designed and other buildings surrounding the site. On the shortest day (Day 350), the old peoples' accommodation on the South and the houses to the South-West of the site were most likely to affect any design proposals with overshadowing (Figure C.7). This suggested placing the school on the North-East part of the site to avoid those shadows.

6.2 Orientation

With reference to the profile presented to the southern aspect, the two shapes, 'SQUARE' and 'TRIANGLE', were examined with respect to a variation of orientation of ± 30° to North-South axis. The result showed that neither shape exhibited any variation over ± 10°. Even over a larger variation of angle, the difference in heating requirements were small. The 'SQUARE' proved less sensitive to variation of orientation than the 'TRIANGLE'. (Further study was presented in the third critique. See Section 4.6 and Figure C.14.)

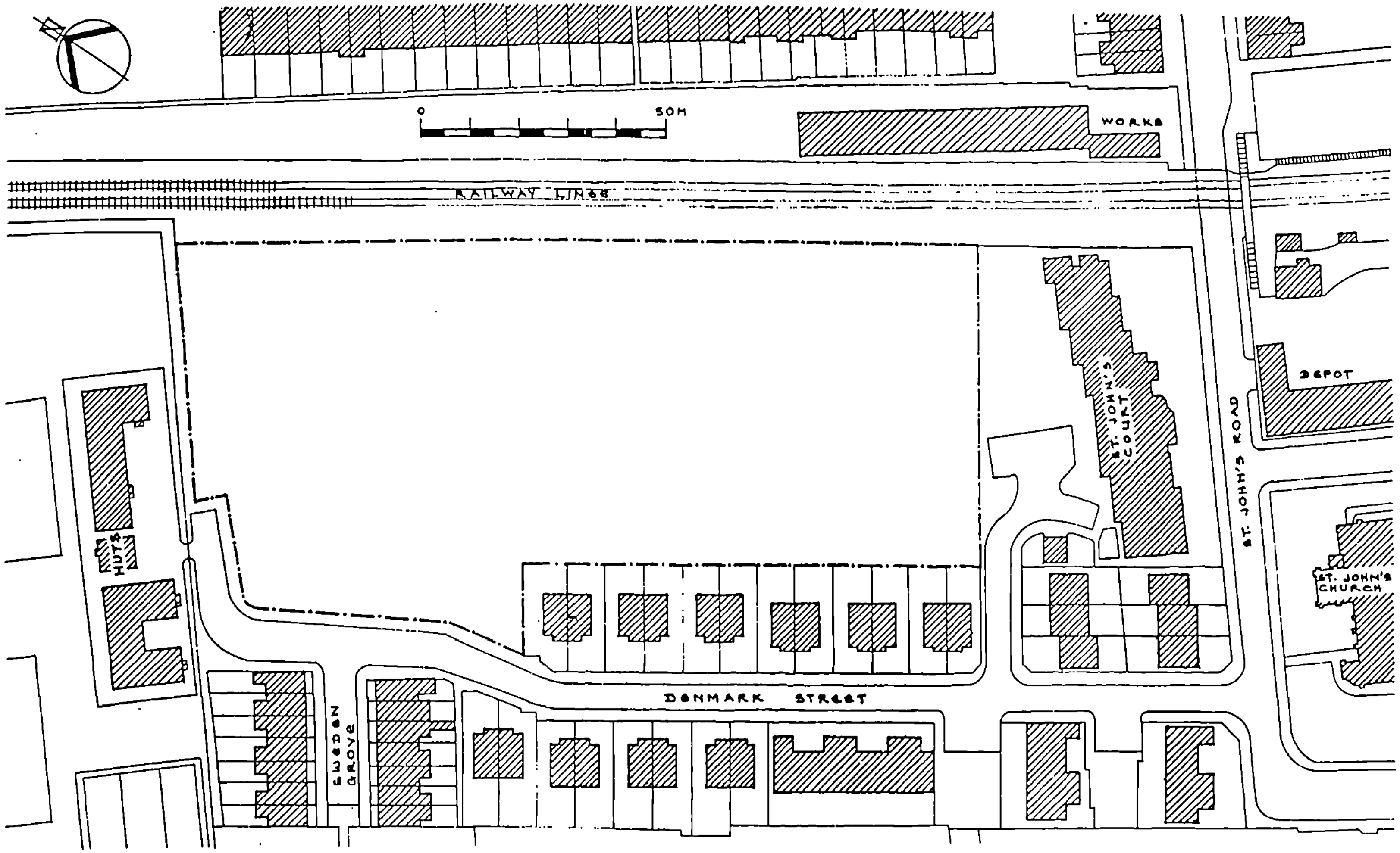


Figure C.6 Plan of the site [Design Note 47]

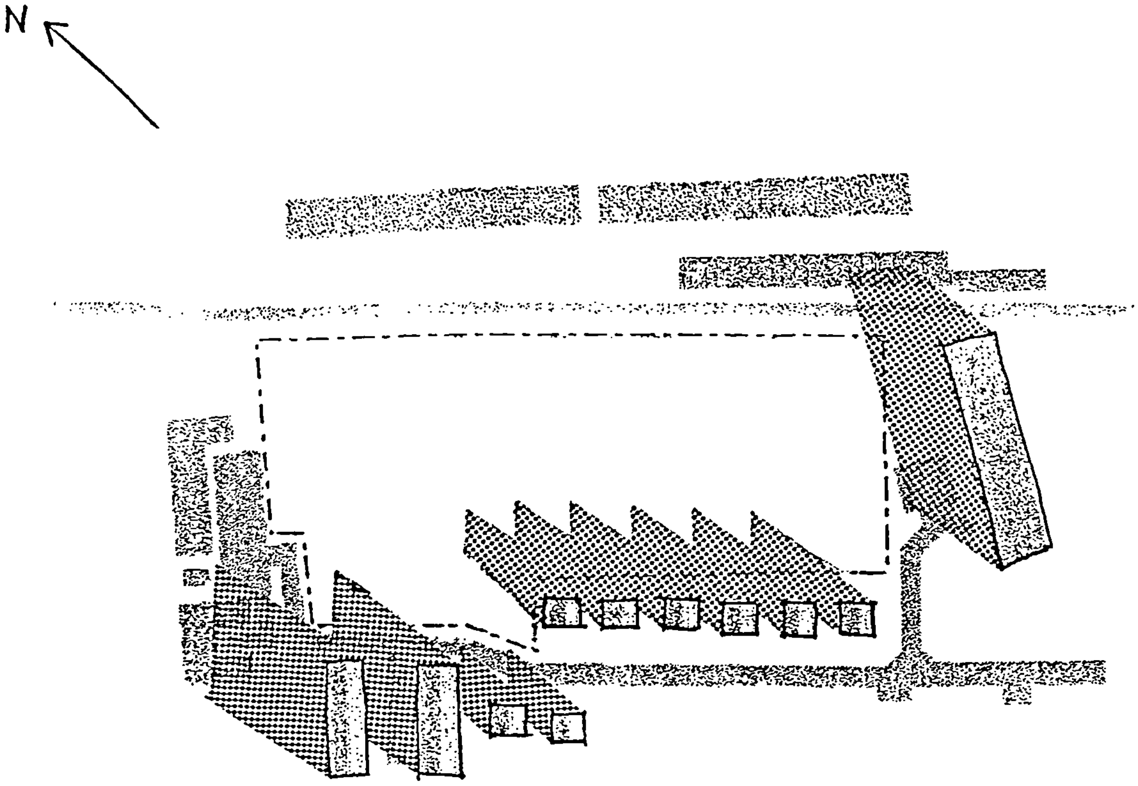


Figure C.7 Shadows created by the buildings surrounding the site

6.3 External requirements

The group considered the external requirements of the brief in conjunction with the shadow avoidance necessary for useful solar gain. The group noted that positioning the building in the North-East of the site would allow a useful large area of recreational space to the South of the site. This location would also create an area for parking and dropping-off points, to the north-west of the building, adjacent to its entrance. Being close to the public highway, only minimal access runs would be required, so that the cost of external works could be reduced. In addition, the school in this position was less likely to lead to objections from the residents of adjoining houses, in terms of noise and view.

6.4 Acoustics

The group gave some consideration to noise from the adjacent railway line. As a result, an earth berm was chosen as the external barrier not only to reduce intermittent noise impact from trains, but also to better contain the site and recreational areas. The group, however, externalised any acoustic control when it examined the construction type, because considering any envelope dedicated to acoustic control might undermine the iterative process of thermal modelling.

7. **Structure and construction** (Part 1)

7.1 Building weight

Thermal simulations performed on *TAS*, using "heavy weight" building envelopes (e.g. brickwork inner leaf, cavity insulation and brickwork outer leaf) and "light weight" building envelopes (e.g. timber frame with insulation, and a brickwork or steel skin outer leaf). The group was interested in both summer and winter conditions in regards to these construction types. More explanation is found in Section 4.2, 'Test Cell Analysis'.

7.2 Materials and Energy

During the brainstorming phase, the group expressed its interest in looking at not only how materials might affect the lifetime energy consumption of the building, but also the embodied energy of the materials themselves. Having considered both Stage 12 of BS8207 and the need to assess the overall energy consequences of any of the materials selected, the group felt that, in order to arrive at a workable solution covering all aspects required in the original brief, less time should be spent looking at the relative energy intensities of the materials, and more time on their thermal performance.

8. **Lighting** (Part 1)

8.1 Initial Daylighting

Initial work on daylighting was based upon exploring daylighting strategy with regard to the users, their needs and the statutory requirements. The group's strategy regarding daylight was:

(i) to exploit daylight as a means of reducing fuel consumption, and

(ii) to use natural light wherever possible.

The group took into consideration the following issues:

* minimum daylight factor of 2 % in all working areas; the group set as its target average daylight factor > 4 %;

* consideration of constraints between thermal and daylighting strategy;

* the importance of high quality natural light in a school;

* need to avoid excessive glare, but need for some contrast for stimulation;

* implications of fenestration design on building form;

* use of shading devices and their influence on daylighting and view.

8.2 Exploration of daylighting strategies on the *Daylight Program*

Having established the strategy, the group undertook its initial work on a simple double class base module (14m * 7m * 2.5m) to assess the result of changing different variables, using the *Daylight Program*. The studies were carried out progressively under different conditions. These, and their results, were as follows:

(i) 40 % glazing on the southern facade (Figure C.8)

There would be thermal and glare implications. A compromise was needed between glazing and the objectionable solar gain. As a result of this, and also because of the thermal considerations in the heating season, the glazed area was reduced to 35 %.

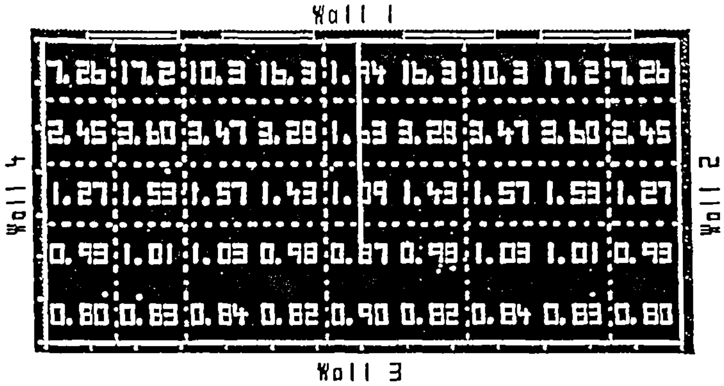
(ii) 35 % glazing and shading devices

The group then re-modelled the module with 35 % glazing on the southern facade (Figure C.9), and subsequently introduced the use of a shading device (a 1m-wide overhang: see Figure C.10). As a result, the amount of solar gain was reduced, but a minimum amount of diffuse solar radiation was gained, thus giving a more uniform distribution of light throughout the class base. The overhang also reduced the risk of glare by reducing the daylight factor near the window. Further development of the overhang will be explained in Section 8.3, (iii) 'Shading devices'.

(iii) Use of rooflights

The group also considered the use of rooflights to improve the uniformity of natural light in the class bases. Introduction of two rooflights (2m * 1m) increased the uniformity ratio, and, at the same time, produced a large increase in the average daylight factor. This indicated that the use of the north-facing rooflight concept would be appropriate to provide diffuse light (Figure C.11).

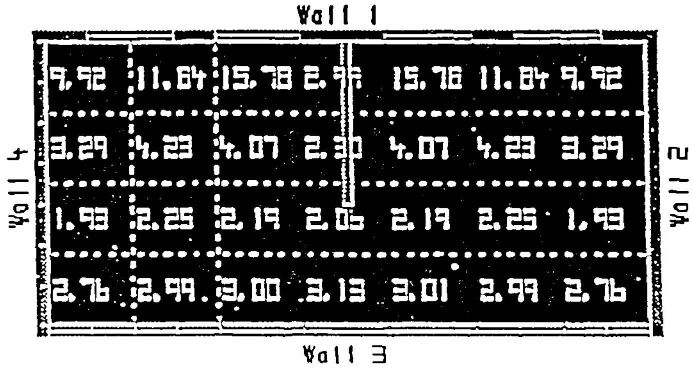
Initial work was also carried out on typical circulation areas in terms of the use of rooflights.



Min.	0.80
Max.	17.18
Average	3.56
Min/max ratio	0.05
Uniformity ratio (min/av.)	0.22

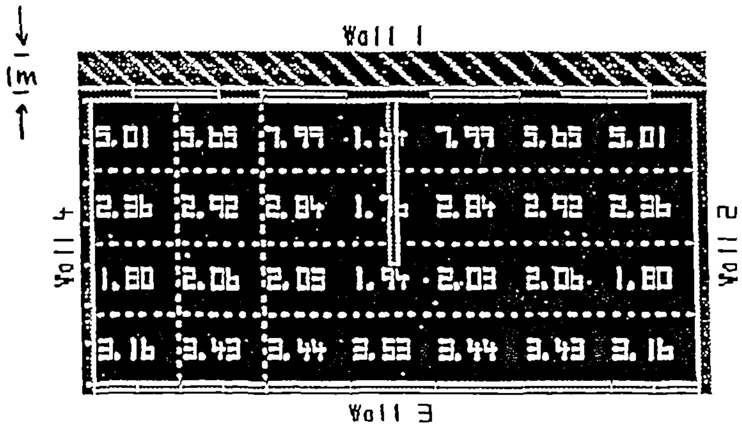
} glare

Figure C.8 40% glazing on the southern facade (unshaded)



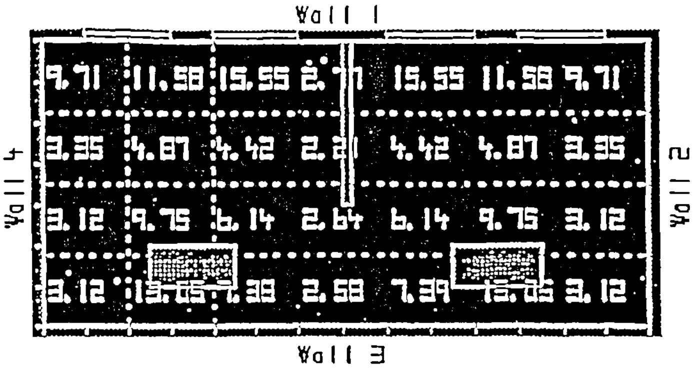
Min.	1.93
Max.	15.78
Average	4.97
Min/max ratio	0.12
Uniformity ratio (min/av.)	0.39

Figure C.9 35% glazing on the southern facade (unshaded)



Min.	1.64
Max.	7.99
Average	3.37
Min/max ratio	0.20
Uniformity ratio (min/av.)	0.49

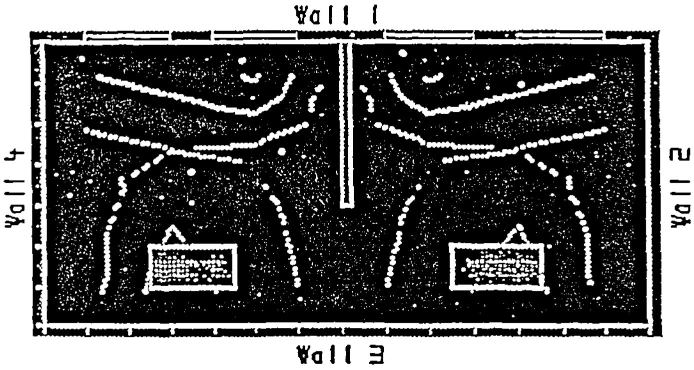
Figure C.10 35% glazing on the southern facade
(shaded by a 1m overhang)



9.71	11.58	15.55	2.[illegible]7	15.55	11.58	9.71
3.35	4.87	4.42	2.21	4.42	4.87	3.35
3.12	9.75	6.14	2.64	6.14	9.75	3.12
3.12	13.05	7.38	2.58	7.39	13.05	3.12

Min.	2.21
Max.	15.55
Average	6.94
Min/max ratio	0.14
Uniformity ratio (min/av.)	0.32

Plan showing daylight contours



Min.	2.21
Max.	15.55
Average	6.94
Min/max ratio	0.14
Uniformity ratio (min/av.)	0.32

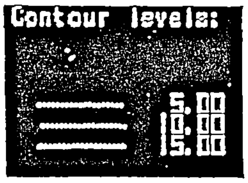


Figure C.11 34% glazing on the southern facade and two rooflights

C.4 The Third Critique and the Final Critique

By the third critique, according to BS8207 Stages 12-20, the group had developed its design proposals, including complete development of the building form and its arrangement on the site, and basic designs of lighting and other services systems. By the final critique the group had developed its scheme design with cost analysis.

4. **Form** (Part 2)

4.4 Roof shapes

The initial building models had simple flat roofs. The group then debated the relative merits of either these or pitched roofs. Following some discussion, the group decided to pursue the pitched roof option with close regard to the materials and thermal properties of any aesthetic decisions made.

Having opted for a pitched roof, the roof forms were developed on both the earlier 'SQUARE' and 'TRIANGLE' models, and later 'SQUARE' (Figure C.12) and 'GEM' (Figure C.13) models (See also Figure C.3). The later two models resulted in the selection of a roof form as well as deposition of rooflights for the final design.

4.5 Final development of the building form: 'SQUARE' and 'GEM'

As a consequence of the tests and simulations explained in Section 4.2 and 4.3, as well as considering the internal layout, two forms were developed, i.e. 'SQUARE' (Figure C.12) and 'GEM' (Figure C.13), oriented approximately on a N/S axis (Figure C.14). Both design forms were modelled in detail with realistic constructions, roof forms, glazing areas, internal layout and internal conditions, and were simulated over 5 representative days, i.e. Day 17, 18 and 50 in winter (Figure C.15 (a)) and Day 232 and 155 in summer (Figure C.15 (c)), as well as a week of severe winter weather (Day 17-19; Figure C.15 (b)). As a result, it was found that during the heating periods the 'GEM' demonstrated a marginally better performance than the 'SQUARE', but in the summer their maximum resultant temperatures were identical. Whilst the group considered the 'SQUARE' a perfectly viable shape, the 'GEM' was selected as the final building form for the following reasons:

(a) marginally better thermal performance;

(b) the internal layout of the 'GEM' offered a better relationship between the hall and other areas;

(c) the mean depth of the building form is lower in the 'GEM' allowing greater potential for natural light; and

(d) the group felt the 'GEM' offered greater aesthetic potential.

The appearance and accommodation plan are shown in Figure C.16 and Figure C.17, respectively. Figure C.18 illustrates the building's arrangement of the site.

4.6 Orientation

Both the 'SQUARE' and 'GEM' plan forms were orientated about the North/South axis for examination of any useful solar gain (Figure C.14). The results of the test are referred to in Section 4.7 'Sensitivity Analysis'.

4.7 Sensitivity Analysis

Using the 'GEM' form, various features were modelled upon the *TAS* for sensitivity. With particular reference to controlling the building's potential for overheating under summer conditions (peak resultant temperatures), the followings were examined:

(i) orientation (see Sections 6.2 in the second critique and 4.6 in the third critique);

(ii) mixed building weight (see Section 7.3);

(iii) glazing area (southern elevation; see Figure C.19); and

(iv) overhangs (see Section 8.3 Final daylighting design, (iii) 'Shading devices').

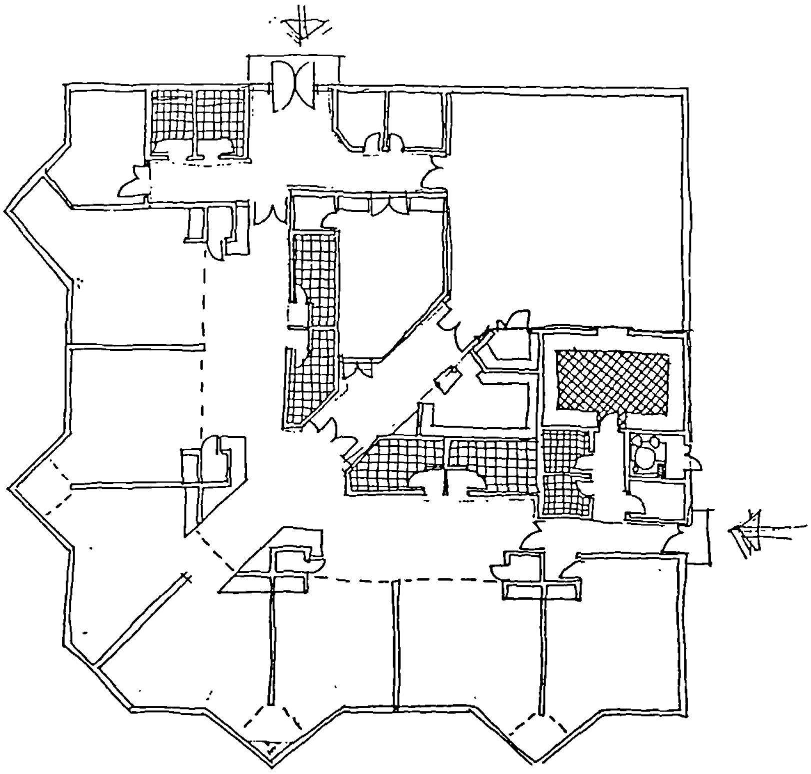


Figure C.12 The 'SQUARE' building form

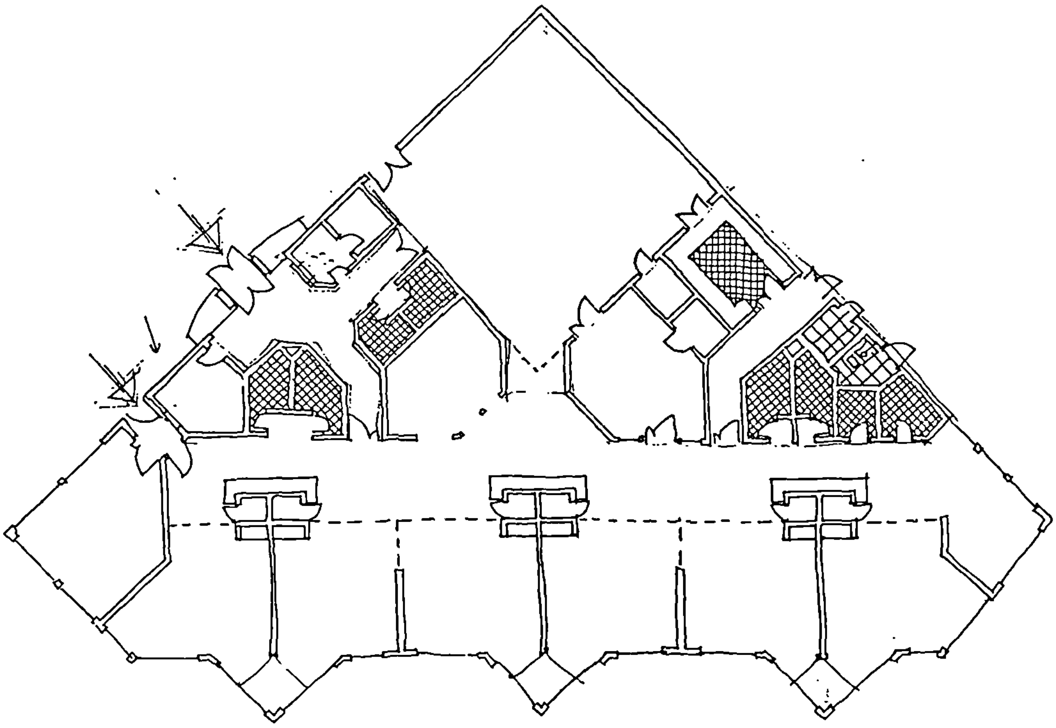
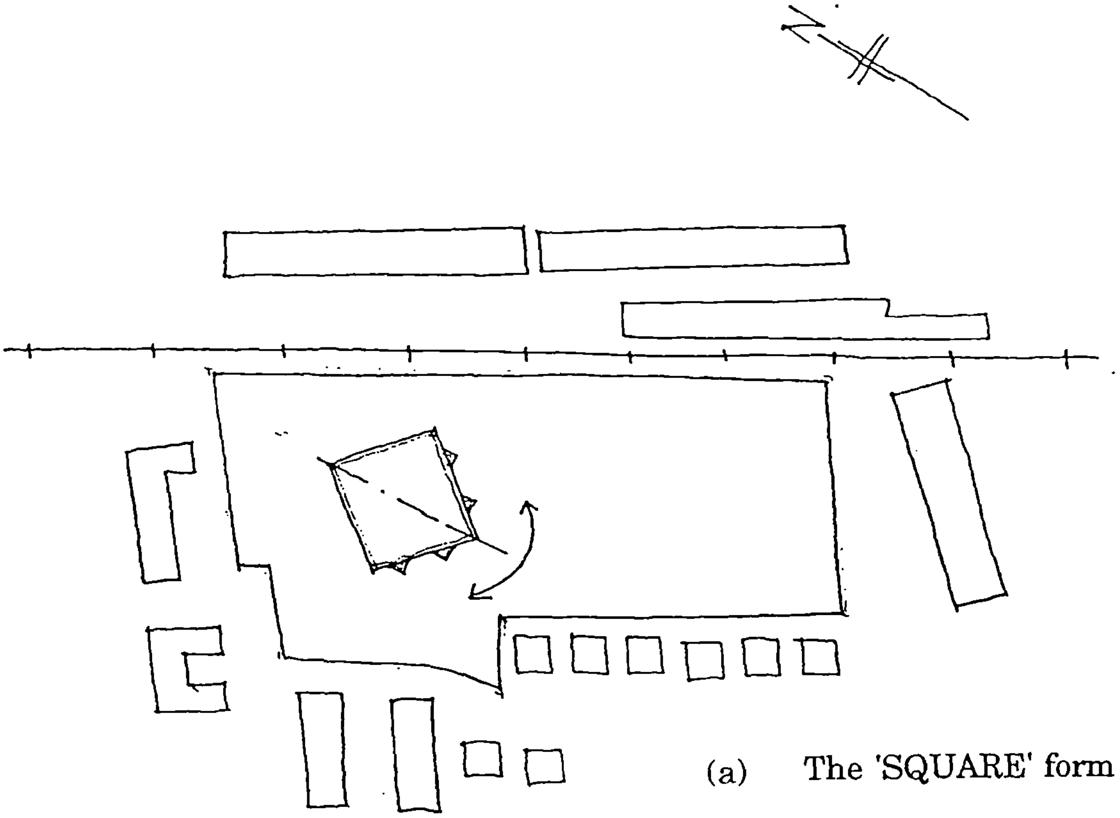
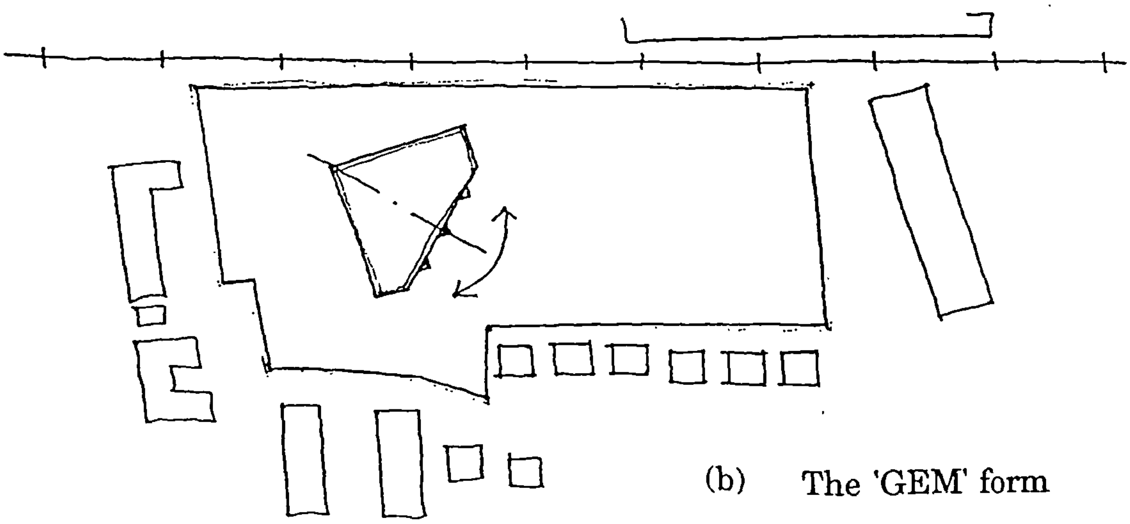


Figure C.13 The 'GEM' building form



(a) The 'SQUARE' form



(b) The 'GEM' form

Figure C.14 Orientation of the building

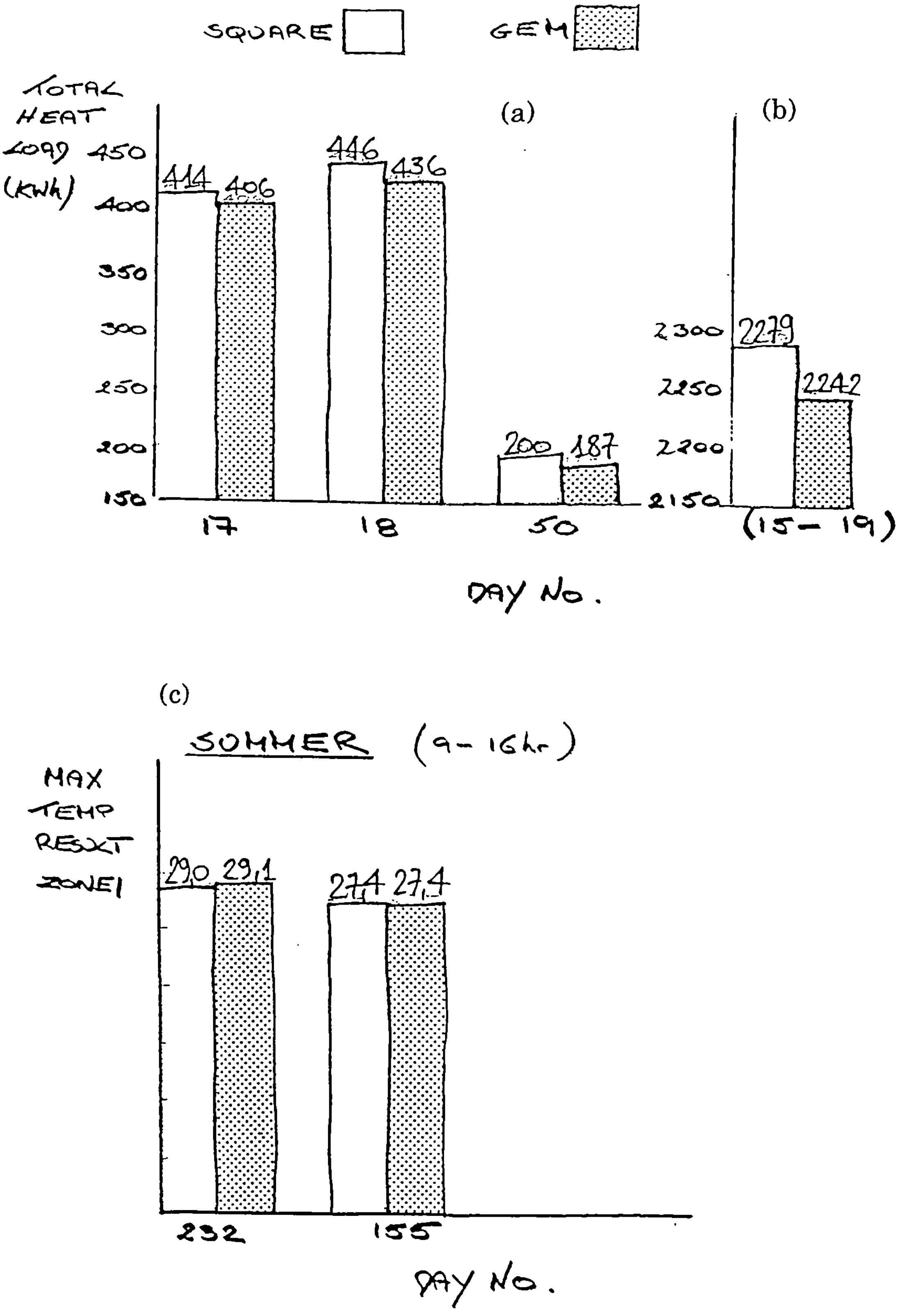


Figure C.15 Thermal comparison between 'SQUARE' and 'GEM'

(a) Day 17, 18 and 50 in winter
(b) A sever week of winter weather (Day 17-19)
(c) Day 232 and 155 in summer

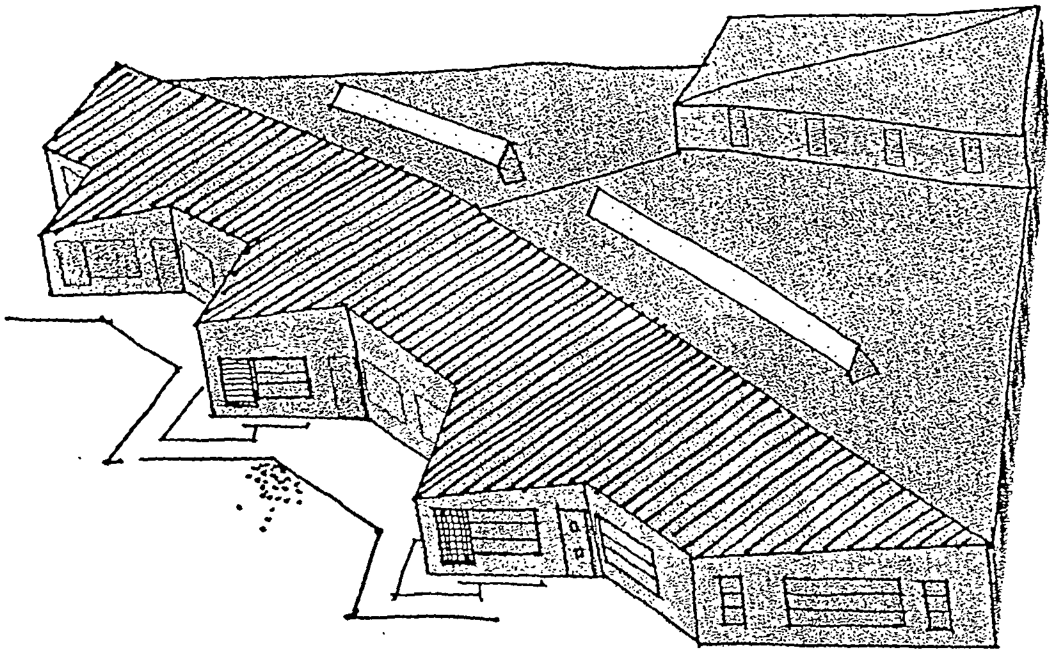
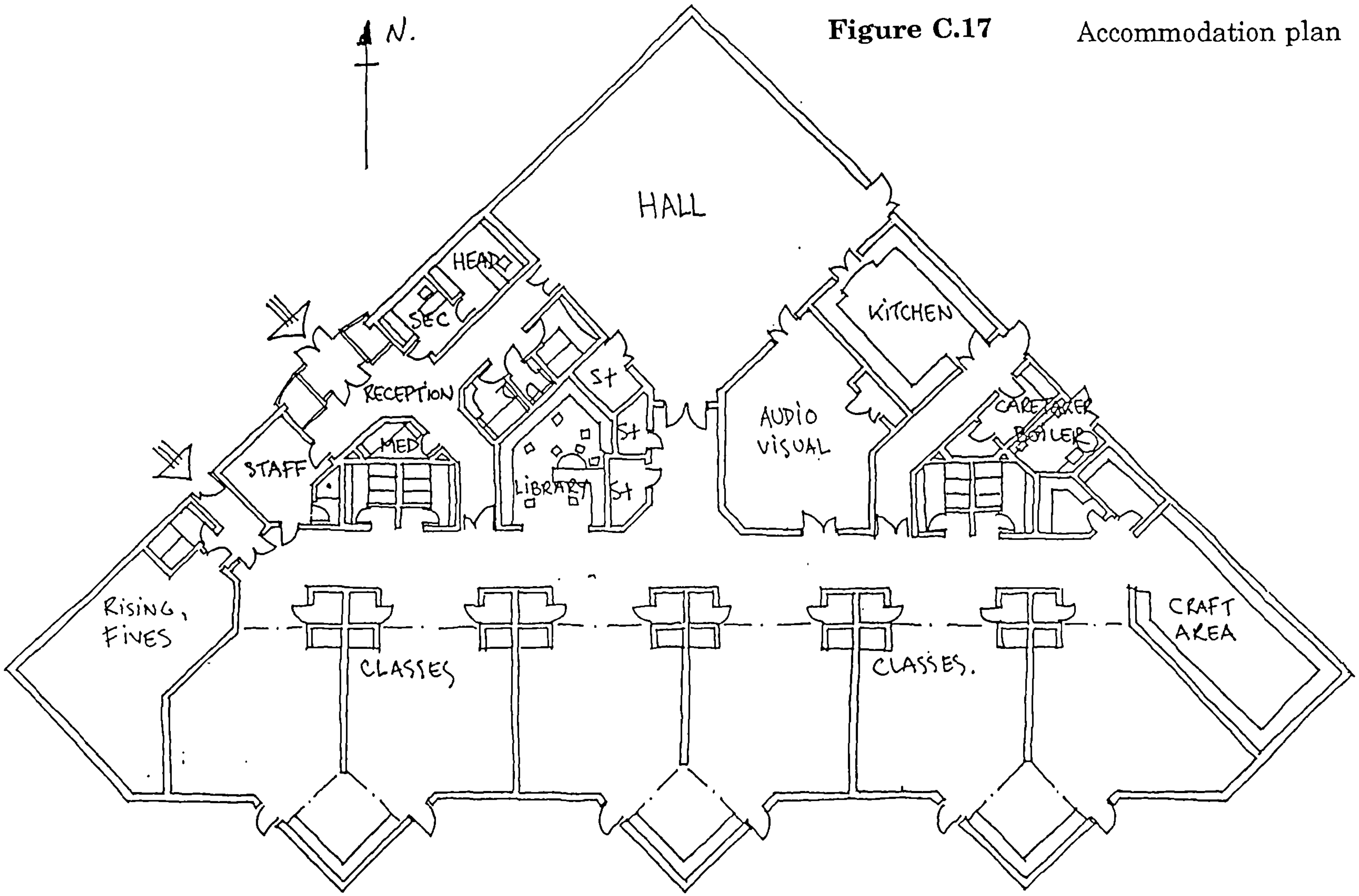


Figure C.16 Appearance of the building

Figure C.17 Accommodation plan



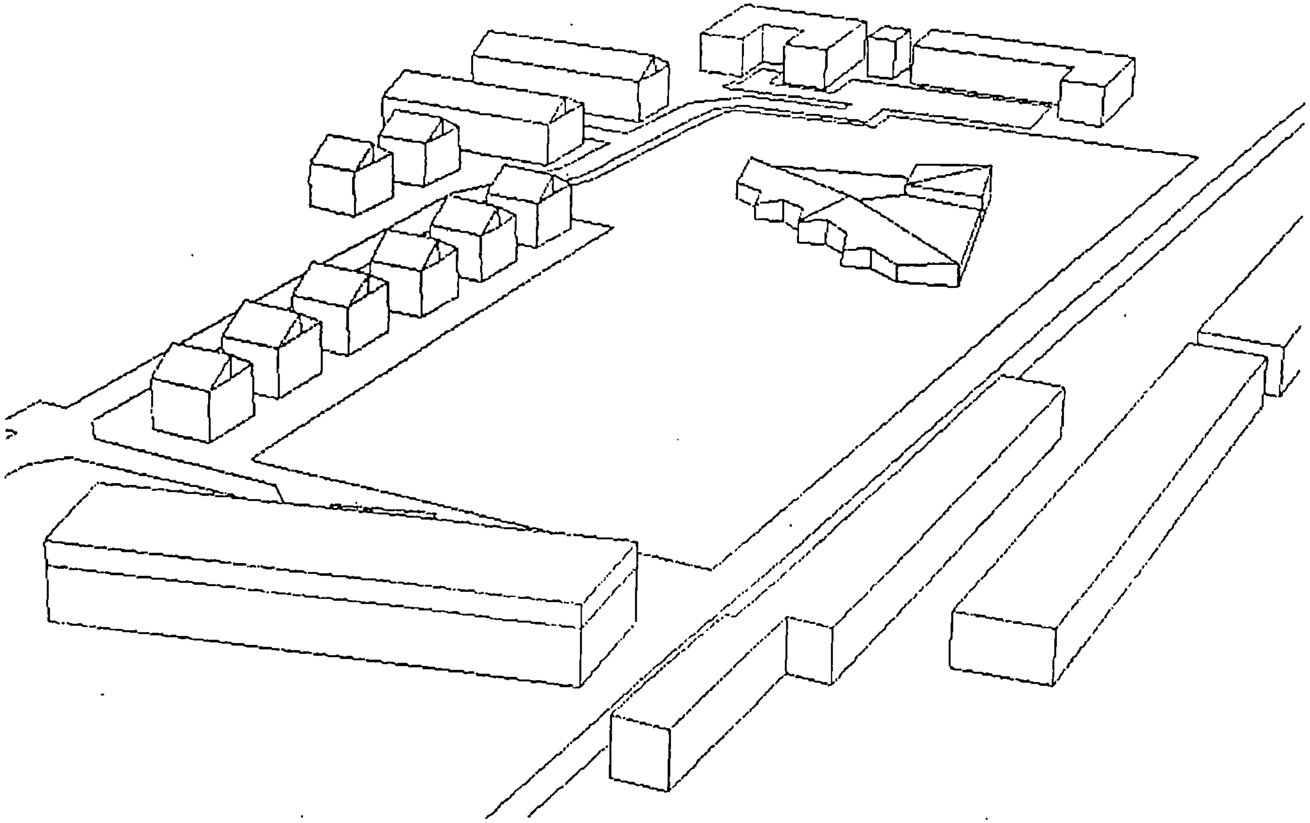


Figure C.18 The building arrangement on the site

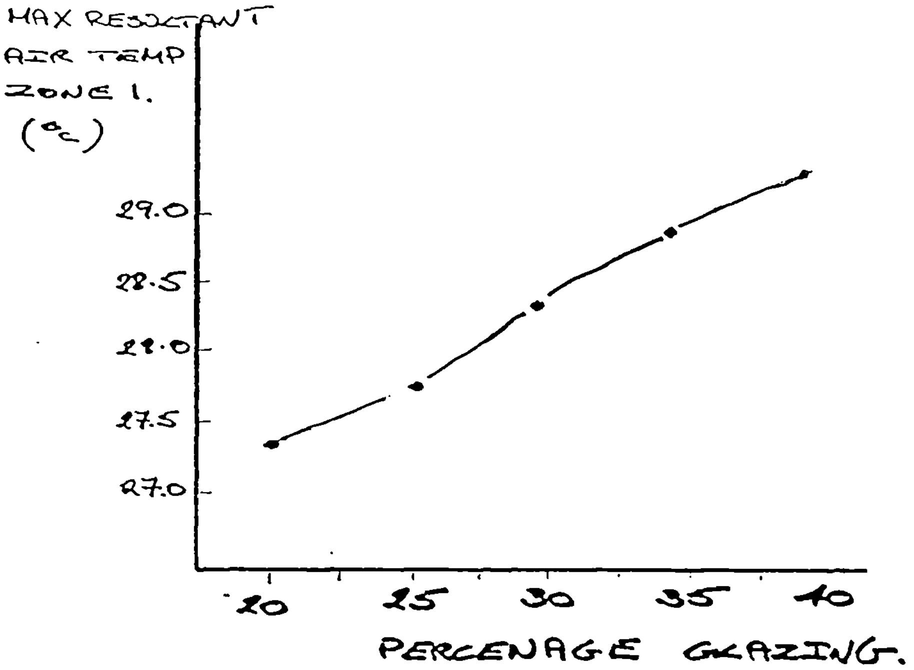


Figure C.19 Effects of glazing area on southern aspect and overheating

4.8 Glazing Types

With specific interest in heating loads, three glazing types, i.e. single, double and low emissivity glazing, were examined under winter conditions. Figure C.20 shows the heating loads on winter days for each glazing type. The group noted that a significant reduction in load between single and double glazing. The additional benefits to be gained from the use of low emissivity glazing on the inner leaf were minimal. Glazing type was examined further under materials and safety.

4.9 Ventilation

Varying the air change rate, the group observed the resultant change in building heat loss in winter and overheating in summer. The test revealed that in summer having an air change rate greater than 5 had very little effect. In winter, the closed building would achieve 0.5 ACH (air change per hour) whilst an average value of 1.5 ACH would be achieved when the children were arriving and leaving. In summer, the air change rate was set at between 3 and 5 volume per hour with windows open.

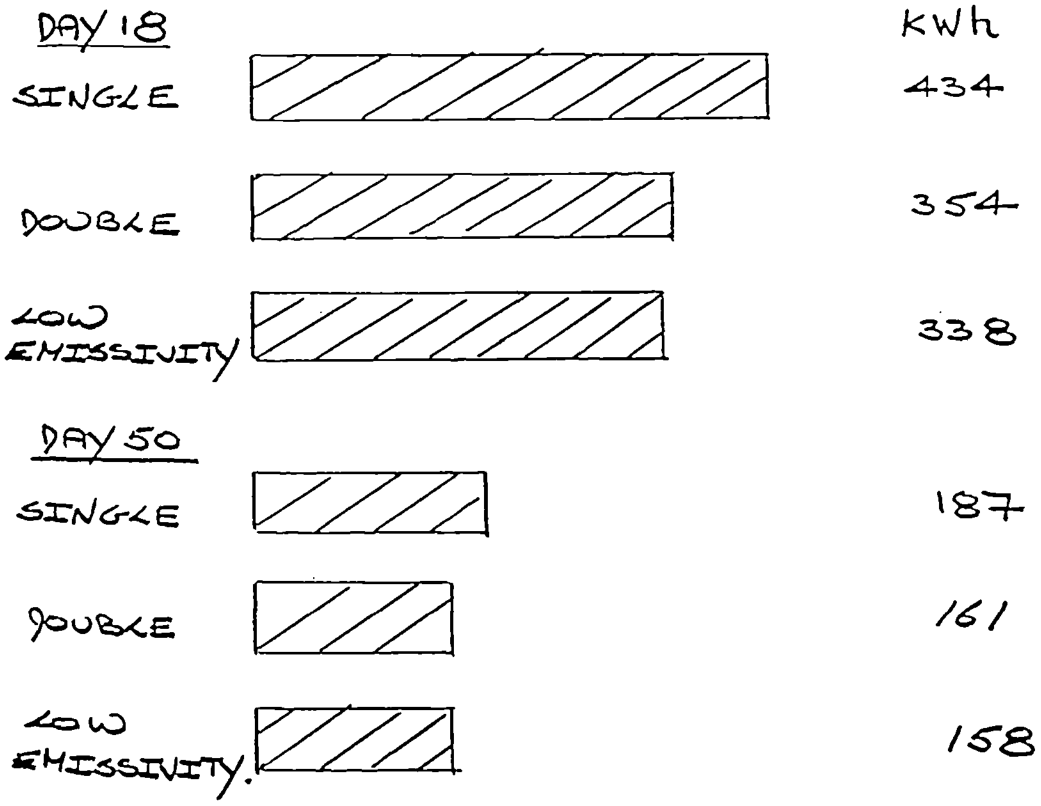


Figure C.20 Glazing type and heating load in winter

7. **Structure and construction** (Part 2)

7.3 Final design

Having tested the various constructions, the group decided to use medium response envelope combining aspects of both "heavy weight" and "lightweight" building, which would best maximise the school's thermal performance.

8. **Lighting** (Part 2)

8.3 Final daylighting design

Having considered the results of the initial work on daylighting design and the relationship between the provision of natural light and the artificial lighting, heating and ventilation, the final fenestration was developed. The final total was 35 % glazing on the Southern facade, and 20 % on the North-East and North-West facades. The details of the main areas were as follows:

(i) Hall

For the high level windows on the North-West elevation, glazing material with transmittance 0.6 would be used to reduce glare. The lower level fenestration would have the glazing with transmittance 0.4 and U-value 2.8 W/mK, because of translucency and safety for activities. On the South-East and South-West walls, there would be high level slot windows with standard transmittance 0.85. As a result, this plan could achieve an average daylight factor of 6 % with a uniformity ratio of 0.58.

(ii) Class bases

Figure C.21 illustrates the window layout on the southern wall of a typical class room, consisting of three sections, 'A', 'B' and 'C'. Section 'A' would comprise of glass blocks with transmittance 0.4. Sections 'B' and 'C' would be standard glazing. In addition, there would be two north-facing rooflights (2m * 1m) with conventional glazing (transmittance 0.85), situated 1m from the rear of the class room (Figure C.22). This arrangement and the surface reflectances of 0.7 for ceiling, 0.5 for walls, and 0.2 for floor, would adequately meet the requirements, as shown in Figure C.23.

(iii) Shading devices

The concept of a shading device running between the protruding shared areas on the Southern facade was then introduced. A 1.5 m device was extremely beneficial in increasing the uniformity of light while maintaining an average daylight factor of approximately 4.9 (Figure C.24). The introduction of a 3m shading device was, however, found to reduce the uniformity (Figure C.25). This suggests that there is an optimum length of shading device in terms of uniformity and average daylight factor. The implications of external view were also recognised. The group opted to use a shading device that would take the form of a trellis running between the shared teaching areas on the front of the class bases. (Thermal testing of shading devices was referred to in the Section 4.7 'Sensitivity Analysis'.)

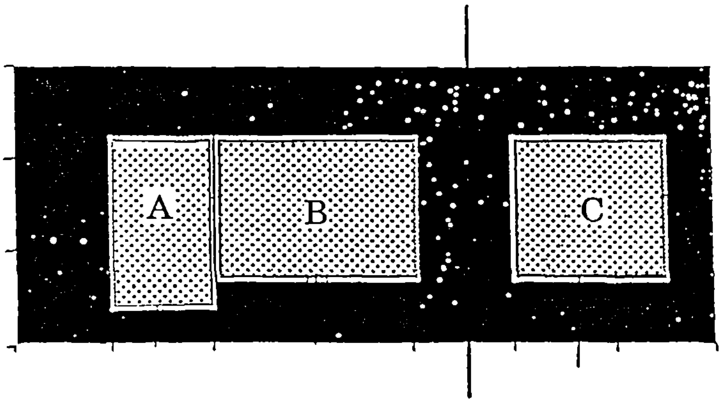
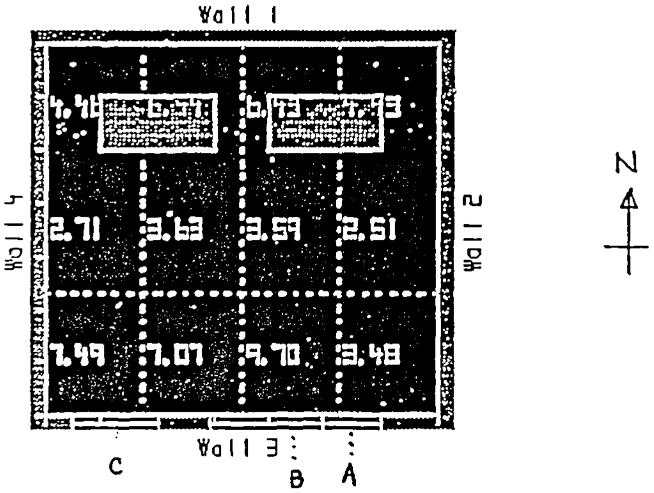
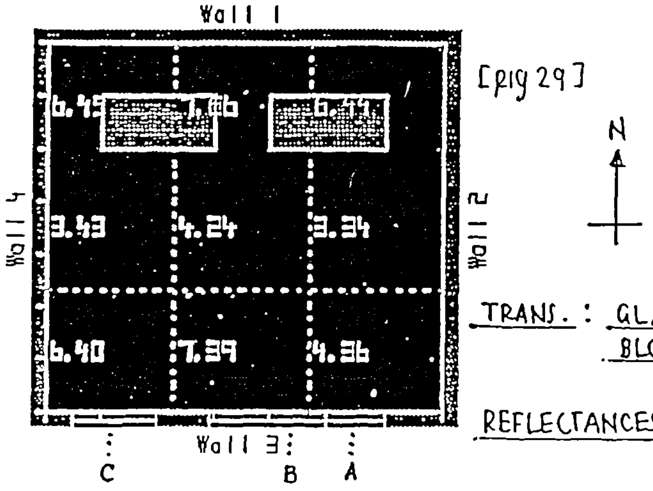


Figure C.21 Window layout on the southern wall of a typical class room



Min.	2.51
Max.	9.70
Average	5.16
Min/max ratio	0.26
Uniformity ratio (min/av.)	0.49

Figure C.22 Plan of daylight factors in a class room (1)



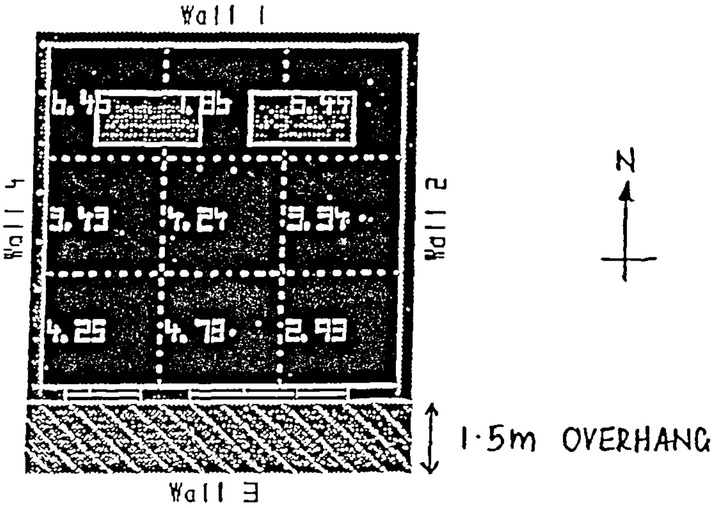
[fig 29]

Min.	3.34
Max.	7.86
Average	5.55
Min/max ratio	0.43
Uniformity ratio (min/av.)	0.60

TRANS. : GLAZING 0·5
BLOCKS 0·4

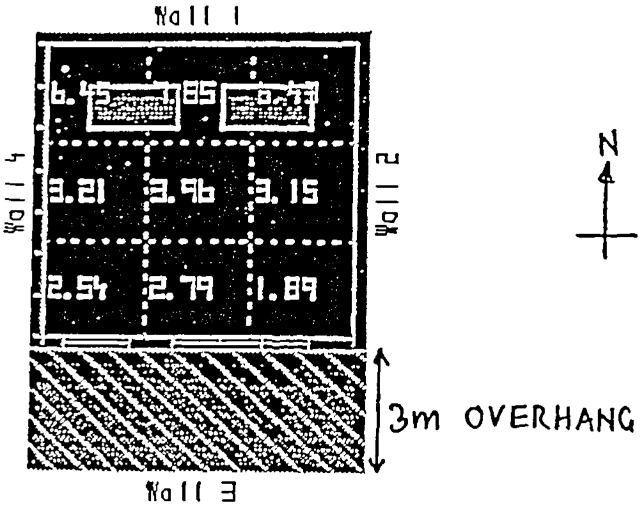
REFLECTANCES INCREASED

Figure C.23 Plan of daylight factors in a class room (2)



Min.	2.93
Max.	7.86
Average	4.86
Min/max ratio	0.37
Uniformity ratio (min/av.)	0.60

Figure C.24 Shading device (1): overhang 1.5 m



Min.	1.89
Max.	7.85
Average	4.25
Min/max ratio	0.24
Uniformity ratio (min/av.)	0.44

Figure C.25 Shading device (2): overhang 3 m

8.4 Artificial Lighting

The group' s strategy for artificial lighting was to explore various systems using the Philips' *Calculux* software package, and to arrive at a recommended system based upon light quality and cost constraints (life cycle costing).

Four systems were investigated. The *Calculux* software was used to model and compare these systems by considering the number of luminaires required to adequately light the class base, the illuminance levels achieved and the power load. In addition to these criteria, the group considered other costs inherent in the system choice on a life cycle costing basis, which takes account of the initial investment and the total running costs per year over the life time of the luminaire. As a result, it would seem economically viable to specify the high frequency version of the TCS312 for the lighting system. The high frequency system should offer advantages over the conventional type in terms of cost and light quality. These are as follows:

* longer life time period (40 years)
* longer re-lamping period
* less frequent maintenance required
* reduced energy consumption (30 %)
* no main flicker
* better colour rendering
* regulate output - potential for energy saving control.

Considering the control system, a simple automatic reset control system would ensure energy-efficient use of lighting. This would include resetting the lights to 'off' at 1300h and 1700h.

9. Safety and security

The group addressed safety issues by examining certain aspects of the design as follows:

Glazing

A child had run into an opened window, and was knocked unconscious. It was, therefore, decided that closable trickle ventilators be installed in the top part of the window frames to avoid this potential danger.

Doors

Vision panels would be located at both adult and child vision levels to allow individuals walking on either side of the door to see each other. All doors should have closers to prevent children closing them on their fingers.

Non-carpeted floors

Non-slip surfaces would be specified.

Vehicular Access

Safety bumps should be provided to reduce speeds in the vehicular access areas.

Fire Access

The car park to the North-West of the building and the play ground to the South would provide fire access. Fire alarm would also be included in the control system.

Security Lighting

This item would be installed due to the high rate of vandalism in the area.

Control System

Cost implications affect the selection and operation of any burglar alarm system.

10. Heading system and control

Space heating

Having considered safety aspects, the group decided on the use of low-temperature cast aluminium framed radiators, served by a gas fired condensing boiler, which would allow the occupants to benefit from a mix of radiant and convective heating, as well as offer flexibility of alternative fuels by the selection of the appropriate boiler.

The group compared two options, i.e. 'one 80 kw boiler' and 'two 40kw boilers', in terms of mean running efficiency and annual saving (see Figure C.26), and selected the latter.

Water heating

To avoid 'dead time' and energy losses over long pipe runs, local electric station water heaters were selected. Frost protection (cold water storage protection) was provided by means of local electric trace heating.

Control system

(i) Zoning

The building is divided into 2 zones enabling restricted usage of the heating system during 'out of hours' activities (Figure C.27).

(ii) Compensated water temperature

The water temperature will be regulated from an external sensor situated on the North-West elevation to avoid 'false' reading as a consequence of unwanted solar gain.

(iii) Optimizers / Frost protection

Unnecessary preheating is avoided by installation of a sensor on the N-W internal hall wall. This sensor will also provide control of frost protection at 5°C.

(iv) Thermostats

Thermostat control motorised radiator values to regulate local area temperatures, and provide reasonable control of thermal comfort.

BOILER COMPARISON

2 × 40 kW | BOILERS IN SAME FINAL MODEL
1 × 80 kW | OVER HEATING SEASON [DN17]

SPECIFIED EFFICIENCIES

Distribution = 90%   Full load = 85%
Stop Loss = 2%

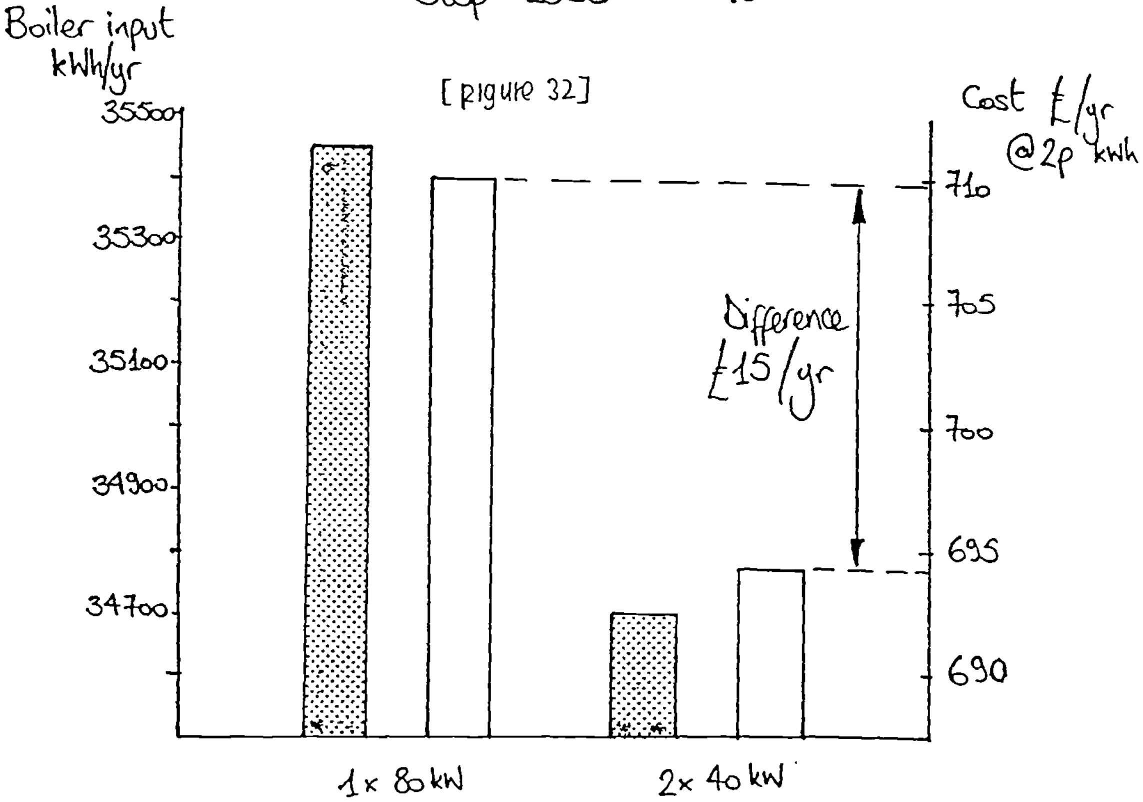


Figure C.26 Boiler comparison

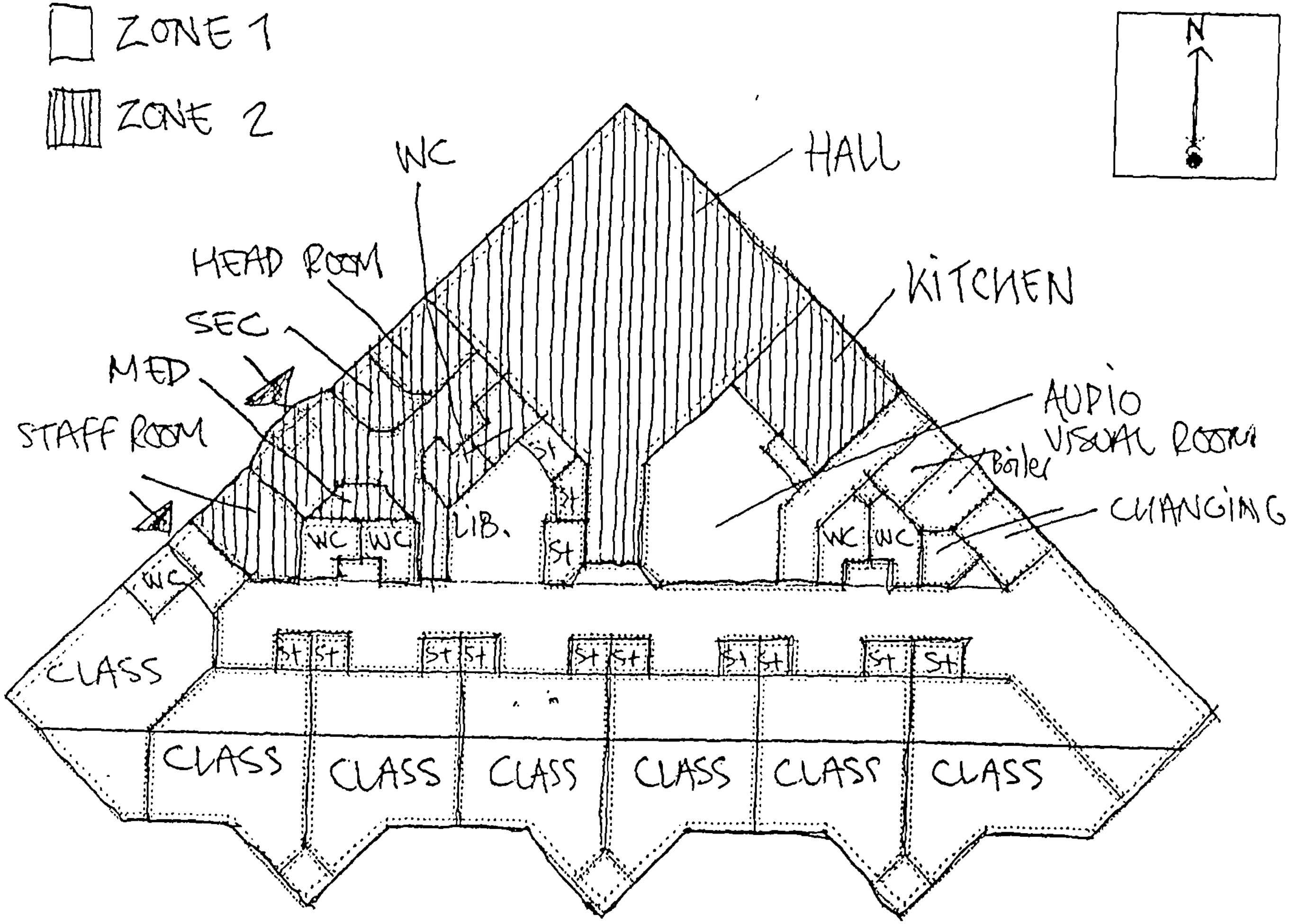


Figure C.27 Two control zones

11. Comfort

The group considered the specific features of comfort and their direct influence on the following issues:

- selection of a rapid response building fabric to reduce the differential temperature between the surfaces and air temperature;
- the installation of double glazing to reduce asymmetric cooling;
- an external trellis reducing summer shortwave radiation through glazing, which also has advantages in reducing glare;
- the fitting of draught-stripping to external opening doors and windows to restrict uncontrolled air movement;
- selection of low temperature panel radiators providing a balanced transfer of heat by radiation and convection;
- installation of high frequency luminaires providing a quality artificial light; and
- design policy of ensuring a good average daylight factor.

12. Building performance

The group carried out an analysis of the building designed in three ways.

(i) Summary of *TAS* simulation

A series of *TAS* simulations formed the basis of the analysis done, allowing design ideas to be tested and to be developed into a final model. The results from the *TAS* analysis are summarised in Table C.3 and, the Sankey diagram illustrates the energy flows into and out of the building (Figure C.28).

Table C.3 Annual Energy Costs

Fuel	Price p/kWh	Consumption $kWh/year$	Cost $£/year$	Cost $£/m^2year$
Gas	2	35,452	709.04	0.65
Electricity	6.6	13,516	892.06	0.81
Totals	-	48,968	1,601.10	1.46

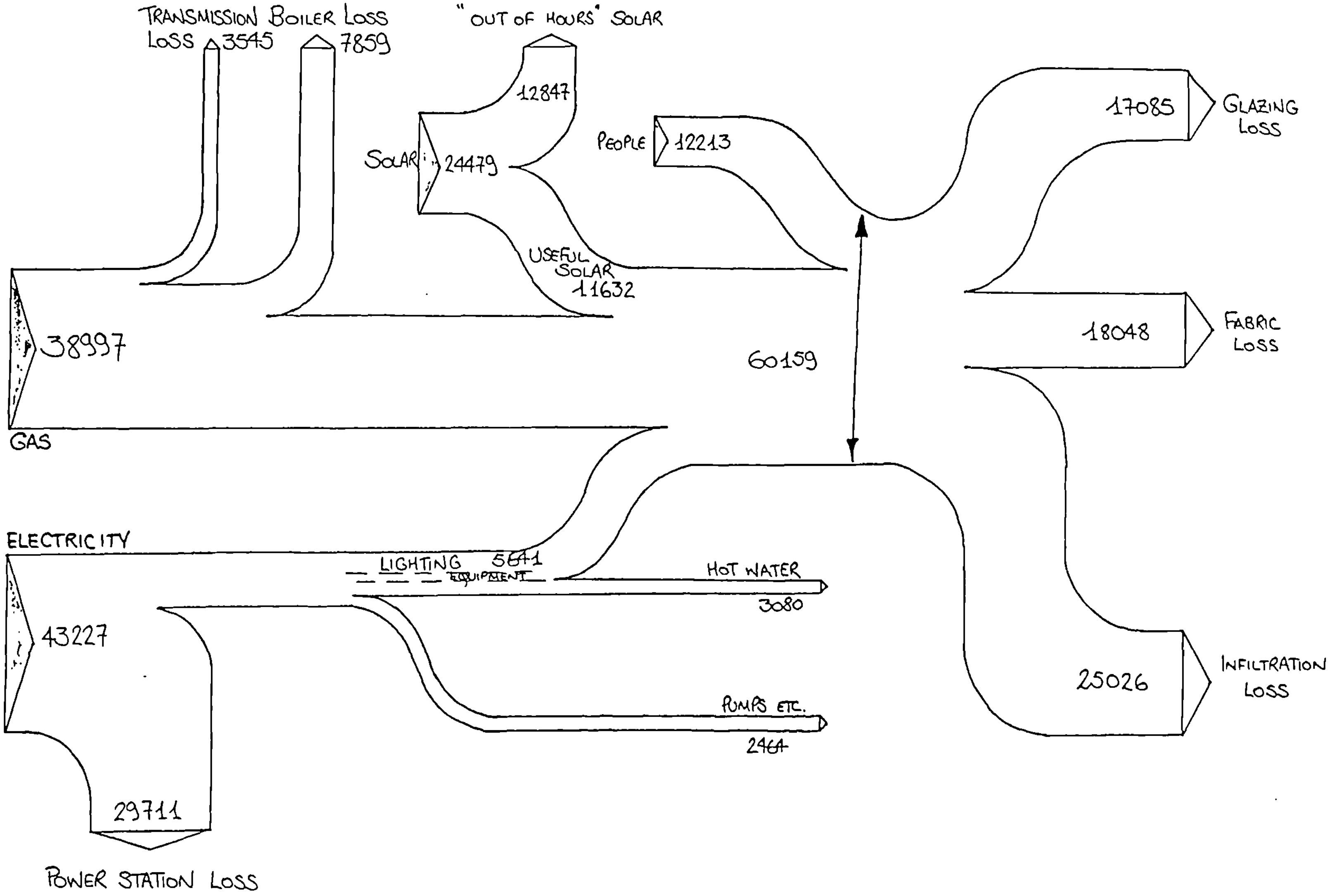


Figure C.28 Sankey diagram for heating season (all values in kWh)

(ii) Comparison of the predicted results for the model against previously monitored schools

Table C.4 Comparison of the predicted results for the model against previously monitored schools

Comparison of Energy Usage and Costs	
Passive Solar 'Montessori' School	£1.52 $/m^2year$
The 'GEM'	£1.46 $/m^2year$
UK circa 1900 stock	1.5 GJ/m^2
Looe Junior and Infant School	0.75 GJ/m^2
Clacton St. John School	0.47 GJ/m^2
The 'GEM'	0.39 GJ/m^2
Comparison of Capital Costs (1986 prices inflated at 7%)	
Looe Junior and Infant School	£625 $/m^2$
The GEM	£529 $/m^2$
Clacton St. John School	£505 $/m^2$

(iii) Design Note 17 calculations

Table C.5 Design Note 17 Calculations

	Standard calculation	% less than target	Solar added calculation	% less than target
EDV (W/m^2)	63.15	16.9	54.47	28.3
AECV (kWh/m^2)	125.19	17.1	107.43	28.9

Note:
DES Maximum Values

Energy Design Value (EDV):	152 W/m^2
Annual Energy Consumption Value (AECV):	302 kWh/m^2

Design Target set at 50% of DES values

Table C.6 Performance Checklist

Building Data

- U Values (W/m^2K)	
External walls	0.409
Roof	0.197
Ground floor	0.280
Glazing	2.675
- Winter Infiltration Rates (Air Change per Hour)	
Closed building	0.5
Key movement times (average)	1.5

Heating

- Annual Heating Requirement (kWh)	27,593
- Annual Heating Cost (£)	710
- Number of days overheating	4

Lighting

- Natural (Average daylight factor %)	> 4
- Artificial (Maintenance average lux)	> 300

Building Capital Cost

- Total cost including VAT (£/m^2)	528.80

C.5 Conclusion

During the course of the case study, the members of design group observed were found to be very good at communicating with each other in a sense that they develop a design working as a team. Their working practice could be characterised as follows:

(a) Common understanding of a brief

The design group held a series of intensive meetings at the beginning of the project, where the members analyzed the brief and developed their design objectives. This suggests that these meetings in which every member of the design group took part allowed to the members to share a common understanding of the brief and design philosophy as well as design objectives.

(b) Individual role play

During the course of the design development, each member of the group was in charge of his own duty, e.g. thermal simulation and daylighting design, using such tools as *TAS*, a thermal analysis system, the *Daylight Program* for daylighting design, and Philips' *Calculux* for designing artificial lighting installations. In other words, the design group established the roles clearly which each member has to play. It was found that this allowed the members of the group to carry out their own duties individually, with reasonable competence, and, eventually, helped the group work efficiently.

(c) Frequent communication

The design group also had frequent meetings throughout the project period in order to organise the individual members' works into a total design solution and conduct their design process. It was found that such meetings allowed important design decisions, e.g. the building form and construction type, to be made by the design group as a whole, rather than one individual member, while alternative design solutions could have been developed by one or a few members.

At the end of the group project, the design which this design group finally presented received the top mark of that year. This case study may suggest that the following issues are some of the keys to a successful design working practice:

(a) Every designer involved in a design project should have a good, common understanding about the brief as well as the design objectives and approach. This could be achieved by involving all members of the design team in the briefing stage.

(b) Whilst each individual designer works with his/her discipline on the basis of the common understanding, all members of the design team should have opportunities to take part in the development of the design by communicating with the others. In this sense, having such meetings at pertinent stages is vital to achieve a quality-assured design within a limited period of time.

Appendix D

Appendix D

ITEMISED KNOWLEDGE UNITS

The building design process was described in terms of the relationships between the *design variables* in Chapter 4. It was considered that the relationships could be described by the expertise embodied, either explicitly or implicitly, within the design methodologies, and such knowledge was involved within the publications which aim to provide 'good practices' concerning particular design issues (Section 4.3.3). Consequently, it was decided to acquire the expertise from available published materials and to itemise it as units of knowledge. This appendix presents the itemised knowledge units, each of which may describe the relationships between two or several *design variables*. These units of knowledge were used to identify the relationships between particular *design variables* so that a checklist for inter-disciplinary design working, and also used as a knowledge source for an intelligent knowledge-based system which demonstrates the checklist.

D.1 Knowledge Sources

In order to allow a particular unit of knowledge to be associated with particular relationships between *design variables*, a *reference number* was given to each of the knowledge units. The reference numbers include the abbreviations which represent the sources of the itemised knowledge. The publications which were used to extract the knowledge, and the abbreviateions are as follows:

"AM"	The Chartered Institution of Building Services Engineers (CIBSE), Application Manual "*Window Design*", 1987
"BS8206_1"	British Standard Institution, BS8206 "*Lighting for Buildings, Part 1 Code of practice for artificial lighting*", 1985
"BS8206_2"	British Standard Institution, BS8206 "*Lighting for Buildings, Part 2 Code of practice for daylighting*", 1992
"UB"	Reid, E., "*Understanding Buildings*", Longman Scientific & Technical, 1984
"BS9207"	British Standard Institution, BS8207 "*Code of practice for Energy Efficiency in Buildings*", 1985
"CIBSE"	CIBSE, "*Code for Interior Lighting*", 1984
"Lecture_93"	Lecture note, "Harnessing Daylight" (Lecturer: Joe Lyne), Mid Career College, London, April 1993
"BRE"	Building Research Establishment (1983), "Lighting controls and daylight use", BRE Digest 272

Some of the units refer to Appendix B, where lighting design methodologies are explained.

D.2 Itemise Knowledge Units

CIBSE Applications Manual *WINDOW DESIGN*

AM[1]
Introduction (1)
It is all too easy to design windows to provide daylight, and at the same time create problems
- unwanted noise intrusion
- glare
- summertime overheating
- energy waste.

AM[2]
Introduction (2)
The Application Manual provides the designers with a means of
- identifying the important factors, and
- solving some of the design problems.

AM[3]
Introduction (3)
The role of the design sequence is
- to prompt the designer when he reaches an impasse, and
- to offer a rational basis for decision making.

AM[4]
Introduction (4)
Some of the techniques presented for designing conventional windows may not be totally reliable when applied to atrium design.
Therefore, caution is urged when applying the content of the guide to anything other than conventional fenestration.

AM[5]
Introduction (5)
Some aspects of window design are beyond the scope of this guide, such as:
- constructional methods, or
- problems of strength or weather tightness.

AM[6]
Stage A1: Site constraints and building form
The priority accorded to daylight & sunlight should be appraised at the initial exploratory stage of design.

AM[7]
A1.1 Priorities
Review anticipated requirements of the accommodation for:
A1.1.1 **Daylight** priorities (B4 Glare)
A1.1.2 **Sunshine** priorities (B4 Glare)
A1.1.3 **View** priorities (B9 View and privacy)
A1.1.4 **Ventilation** priorities (A1.2.5.3 Wind)
A1.1.5 **Sound** insulation priorities (B8 Noise)

AM[8]
A1.1.1 Daylight priorities (0)
Establish whether daylight is
(i) *Essential,*
(ii) *Desirable,*
(iii) *Unimportant,*
(iv) *To be restricted* or *excluded.*

AM[9]
A1.1.1 Daylight priorities (1)
(i) *Essential,* i.e. necessitating roof lighting or shallow side-lit interiors with plan form and siting offering minimal external obstruction.

AM[10]
A1.1.1 Daylight priorities (2)
(ii) *Desirable,* i.e. daylight is preferred but supplementary artificial lighting during daylight hours will be acceptable.

AM[11]
A1.1.1 Daylight priorities (3)
(iii) *Unimportant,* i.e. plan form and siting are virtually unrestricted by daylighting considerations.

AM[12]
A1.1.1 Daylight priorities (4)
(iv) *To be restricted* or *excluded,* i.e. specific requirements may operate which call for the control or avoidance of daylight.

AM[13]
A1.1.2 Establish sunshine priorities (0)

- Orientation for sunshine must usually be balanced against other requirements.
- Surrounding buildings / topographical constraints will reduce the potential maximum.
- The designer must seek the best compromise by reference to sun path diagrams, and bear in mind any recommendations for minimum duration.
- *Limitation* or *Exclusion.*

AM[14]
A1.1.2 Establish sunshine priorities (1)
A1.1.2.1 Limitation:
Limitation will generally be needed at some time of the day and year. Some forms of permanent screening may be acceptable, but adjustable screening will allow maximum access of daylight on dull days.

AM[15]
A1.1.2 Establish sunshine priorities (2)
A1.1.2.2 Exclusion:
When sunshine is to be permanently excluded, glazing should preferably be oriented due north. (see B12 Shading devices)

AM[16]
A1.1.3 View priorities (1)
The activity within a particular space or the nature of the external scene may make the provision of view:
(i) *essential*,
(ii) *desirable*, or
(iii) *unnecessary / undesirable.*
(See B9 View and privacy)

AM[17]
A1.1.3 View priorities (2)
If view requirements constrain orientation, examine compatibility with requirements for sunshine.

AM[18]
A1.1.4 Ventilation priorities (1)

- Air change and air movement, particularly for summer comfort, can be achieved by openable windows.
- However, room depth (if the space is lit from one side) may preclude natural ventilation, or

AM[18']
A1.1.4 Ventilation priorities (2)

- External noise level may demand fixed glazing.
- When fenestration is fixed or must remain unopened, it is particularly important, unless facing north, that glass area should be shaded and of an appropriate area. (See A1.2.5.3 Wind)

AM[19]
A1.1.5 Sound insulation priorities

- Current or potential external ambient noise levels may call for precautions against noise intrusion, or internally generated noise may need to be constrained within the building.
- If restricted and fixed fenestration is considered, consider also the implications for lighting and ventilation. (B8 Noise)

AM[20]
A1.2 Site constraints (0)

- The ambient environment, including surrounding development, usually constraints **building form**, **siting** and **orientation**.
- These constraints have consequences for fenestration, and
- may determine the extent to which the development can be naturally lit or receive direct sunlight.

AM[21]
A1.2 Site constraints (1)
A1.2.1 Planning directives
Planning directives may confine the building envelop within:

- predetermined building lines
- height restrictions. (e.g. Local planning authority)

AM[22]
A1.2 Site constraints (2)
A1.2.2 Fire precautions (e.g Building Regulations 1985)

The amount of glazing in external walling (i.e. window apertures) may be restricted to reduce the risk of the spread of fire to adjacent property. Maximum permissible window area depends on:

- the distance between buildings
- combustibility of the opaque of the external walling of the bldg.
- the presence of other 'unprotected' areas such as doors
- the classification of the building
- area and volume of the building etc.

AM[23]
A1.2 Site constraints (3)
A1.2.3 Adjoining owners (0)

These may constrain built form near site boundaries.

A1.2.3.1 Rights to light
A1.2.3.2 Rights to sunshine
A1.2.3.3 Privacy

AM[24]
A1.2 Site constraints (4)
A1.2.3 Adjoining owners (1)
A1.2.3.1 Rights to light

The windows of adjoining buildings could be seriously deprived of daylight by certain forms of new development. The adequacy of the available daylight will be judged according to circumstances, but is generally considered sufficient if, after infringement, half the room over a horizontal reference plane at a height of 0.85m above floor level lies within the 0.2% sky factor contour.

AM[25]
A1.2 Site constraints (5)
A1.2.3 Adjoining owners (2)
A1.2.3.2 Rights to sunshine

Adjoining property may also be deprived the sunshine by new development.

AM[26]
A1.2 Site constraints (6)
A1.2.3 Adjoining owners (3)
A1.2.3.3 Privacy

New development may result in unacceptable intrusion into the privacy which owners of surrounding property might reasonably expect to enjoy. Fenestration therefore need to be excluded from certain positions in the cause of good neighbourliness.
(See B9 View and privacy)

AM[27]
A1.2 Site constraints (7)
A1.2.4 Topographical constraints

The effectiveness of the fenestration is limited by obstructions, natural/man-made, present/future. Examine the topography of the site and its surroundings for existing or potential obstruction to sunshine and daylight, bearing in mind the effects of sloping ground and height above ground on the receipt of sunlight.

- A1.2.4.1 North facing slopes
- A1.2.4.2 South facing slopes
- A1.2.4.3 Overshadowing
- A1.2.4.4 Angular height and width

AM[28]
A1.2 Site constraints (8)
A1.2.5 Ambient environment (0)

Ambient noise level and the atmospheric environment have consequences for

- glazed area
- window design
- maintenance
- the opportunity for natural ventilation.

AM[29]
A1.2 Site constraints (9)
A1.2.5 Ambient environment (1)

The ambient environment should be reviewed for conditions which:

- may call for **reduced glass area** or **fixed windows** and
- may have consequences for the choice of **architectural form**.

(See AM[29'])

AM[29']
A1.2 Site constraints (10)
A1.2.5 Ambient environment (1')

e.g. **Shallow daylit** rooms **facing a south direction** whose windows must be **permanently closed** may need **air conditioning** to establish comfort conditions in summer.

e.g. Under these circumstances **deeper, artificially lit** and **mechanically ventilated** interiors with **windows serving primarily as view apertures** may offer a better solution for plan arrangement, internal environment and energy demand.

AM[30]
A1.2 Site constraints (11)
A1.2.5 Ambient environment (2)
A1.2.5.1 Airborne noise (1)

The **position**, **area** and **type** of glazing are affected by the need for sound insulation against airborne noise from external sources, or through containment of noise generated within the new building(s). (See B8 Noise)

The acceptable limits of intruding noise depend on the activities within the building.

AM[30']
A1.2 Site constraints (12)
A1.2.5 Ambient environment (2')
A1.2.5.1 Airborne noise (2)

When effective sound insulation is essential, the peak pressure levels over the audible spectrum should be recorded:

(a) Surface traffic;
(b) Air traffic;
(c) Noise Abatement Zones

AM[31]
A1.2 Site constraints (13)
A1.2.5 Ambient environment (3)
A1.2.5.2 Atmospheric pollution (1)

In very dirty or polluted localities, sealed windows and mechanical ventilation (or air conditioning) may be necessary.

AM[31']
A1.2 Site constraints (14)
A1.2.5 Ambient environment (4')
A1.2.5.2 Atmospheric pollution (2)

The deposition of dirt on the exterior of glazing requires compensatory increases in glass area depending on the slope of the glazing and frequency of maintenance. (See Table B1.3: Correct factors for glazing)

AM[31"]
A1.2 Site constraints (15)
A1.2.5 Ambient environment (4")
A1.2.5.2 Atmospheric pollution (3)

In heavily polluted areas, or where dirty processes occur, rooflights will be inefficient unless cleaned frequently.

AM[32]
A1.2 Site constraints (16)
A1.2.5 Ambient environment (4)
A1.2.5.3 Wind (1)

- Wind is relevant on exposed sites and for buildings which stand well above the general roof level of surroundings. Conduction and infiltration losses are then increased, and natural ventilation may prove difficult to control satisfactorily.
- Consider, therefore, the advisability of using fixed glazing or reducing the glazing area in exposed positions if the site is subject to strong winds or where the proposed building will be much taller than its surroundings.

AM[33]
A1.2 Site constraints (17)
A1.2.5 Ambient environment (5)
A1.2.5.3 Wind (2)

The effect of tall buildings on the wind environment in the surrounding areas at ground level should also be borne in mind. An unacceptable deterioration in predicted local wind climate may call for:

- a reduction in building height,
- an increase in building depth, or
- a change in orientation with consequences for environmental servicing and fenestration.

AM[34]
A1.2 Site constraints (18)
A1.2.5 Ambient environment (6)
A1.2.5.4 Precipitation

Some configurations of roof glazing may encourage the deposition of snow with consequent increase in roof loading and diminution of daylight admitted. This should be considered in localities subject to heavy snowfall.

AM[35]
A1.3 Building form and siting (0)

In exploring the massing & siting of alternative plan arrangements, the consequences for:

- **daylighting**;
- the receipt of **sunlight**, and
- the **overshadowing** of surroundings

need to be assessed broadly and quickly.

AM[36]
A1.3 Building form and siting (1)
A1.3.1 Access to skylight (1)

To ensure the full daylighting of work spaces, the fenestration and external obstruction should be such that a direct view of some sky is available to the whole of the reference plane. (see A2.2.2 Depth check)

AM[37]
A1.3 Building form and siting (2)
A1.3.1 Access to skylight (2)

The illuminance flux entering a window is approx. proportional to the vertical angle θ subtended by the sky visible from the centre of the window. The effective value of θ is determined by decisions made at this stage on the siting & massing of the proposed building. (see Figure A1.2)

AM[38]
A1.3 Building form and siting (3)
A1.3.2 Access to sunlight

Confirm that the **requirements for access to (or exclusion of) sunlight** can be achieved in the layout under consideration:

(a) Review sun position with respect to facades using sunpath diagram appropriate to the latitude of the site.
(b) For facades where the criterion adopted is based on receipt of a specified number of hours of potential sunlight at a stated time of year, apply DoE type sunlight indicator.
(c) For total hours of insolation (potential or probable) at a critical point, derive the obstruction overly with respect to that point and superimpose, correctly oriented, on appropriate sunpath diagram. (see B3 Sunlight)

AM[39]
A1.3 Building form and siting (4)
A1.3.3 Overshadowing (1)

Consider **overshadowing** by the proposed building form. This may have important consequences for:

- the usefulness of external spaces in fine weather,
- the microclimate throughout the year (plant growth etc.),
- the insolation of facades and roof surfaces for potentially useful solar gain during the cooler months.

AM[40]
A1.3 Building form and siting (5)
A1.3.3 Overshadowing (2)

Consider whether the overshadowed area can be diminished or arranged to occur at times of least inconvenience. Can

- building height,
- plan shape,
- profile, or
- orientation

be amended without detriment to the desired standard of daylight, sunshine, or view?"

AM[41]
A1.3 Building form and siting (6)
A1.3.3 Overshadowing (3)

To examine the extent of shadowing and the consequences of change in building position and profile, consider:

(a) Plan form of cast shadows at selected critical times. (see B3 Sunlight)
(b) Check on potential sunlight availability at selected critical places. (see A1.3.2 (c))
(c) Model studies, permitting review of potential daily shadow pattern at chosen times of the year. (see B3.7 Site analysis)

AM[42]
A1.3 Building form and siting (7)
A1.3.4 Thermal considerations (1)

Full daylighting may have unacceptable thermal consequences, but rational decisions on fenestration for energy conservation and thermal comfort can only be made in clearly defined situations.

AM[43]
A1.3 Building form and siting (8)
A1.3.4 Thermal considerations (2)

At the exploratory stage of design, it must suffice to recognise certain thermal constraints (that may eventually limit the glazed area):

(a) In heated spaces, **north facing glazing** should have the minimum area compatible with acceptable daylighting or view.

(b) The net seasonal heat loss through south facing glazing is not so sensitive to changes in glazed area, and there is less constraint on size, although the night-time peak heat loss will be the same as for north facing glazing and the solar gain in summer could be excessive without shading, causing thermal discomfort and, in air conditioned spaces, increased energy demand.

AM[44]
Design sequence (Summary)
Stage A1 Site constraints and building form
Consider

- the requirements for daylight and sunshine
- the potential constraints

Stage A2 Rooflight and window sizing

- Establish the appropriate ADF targets;
- Find the amount of glazing required.

AM[45]
Stage A2 Rooflight and window sizing

Having considered broadly the requirement for daylight and sunshine and the potential constraints, the next stage is to establish the appropriate average daylight factor targets and to find the amount of glazing required.

The designer should consider the potential of **rooflighting** first; where illuminance over the working plane is the primary concern (and the area is large), this form of lighting is generally the most effective provided that:

- the admission of direct sunlight,
- excessive solar gain can be controlled, and
- the glazing can be cleaned easily.

AM[46]
Stage A2 Rooflight and window sizing

Side windows may enhance the **appearance** of objects within the room more effectively than rooflights.

AM[47]
Stage A2 <u>Rooflight and window sizing</u>
(1) A2.1 Rooflights:

If rooflighting is acceptable, the type of rooflight and the area of glazing necessary should be determined by the sequence provided in Stage A2.1 (Fig. A2.1).

A2.1.1 Rooflighting profiles
A2.1.2 Choice of glazing material
A2.1.3 Estimate of glazing required

(2) A2.2 Side windows

Where daylighting is to be provided by side windows alone or by side windows supplemented by rooflights or artificial lighting, the glazed area is obtained as described in Stage A2.2.

A2.2.1 Specify window glazing material
A2.2.2 Check depth of room
A2.2.3 Estimate area of window glazing required

(3) Stage A3:

To review the most effective shape and position for these windows, the designer then proceeds to Stage A3.

AM[48] None

AM[49] None

AM[50]
A2.1 <u>Rooflights</u> (0)

Side windows alone cannot provide adequate daylight penetration in **deep interiors** (A2.2.2 Depth check).

Rooflights (other than those illuminating atria) can light only the top floor of a multistorey building, so overall lighting may demand **single-storey construction**.

AM[51]
A2.1 Rooflights (1)
A2.1.1 <u>Rooflighting profile</u> (1)

(i) For flat or low-pitched roofs, **barrel** rooflights or **horizontal rooflights**.
(ii) For wider spans **shed rooflights**.
- All the above provide a high daylight factor for a given area of glazing, but invite solar gain problems in summer. (see Figure A2.2)

AM[52] A2.1 Rooflights (2)
A2.1.1 <u>Rooflighting profile</u> (2)

(iii) Where solar gain would be disadvantageous **sloping sawtooth** or **vertical sawtooth**; these must face away from the equator.
- Directional lighting may restrict layout of machinery. (see Figure A2.2)

AM[53]
A2.1 Rooflights (3)
A2.1.1 <u>Rooflighting profile</u> (3)

(iv) Where sawtooth profile is unacceptable **monitor rooflights**, such as vertical symmetrical monitors, sloping symmetrical monitors or asymmetrical monitors. (see A2.1.4 Rooflight positions)

AM[54]
A2.1 Rooflights (4)
A2.1.2 <u>Choice of glazing material</u>
Consider:

- maintenance characteristics (effects of weathering, etc.)
- light transmittance
- thermal transmittance (U-value)
- solar gain factor / shading coefficient
- safety (glazing may need wired glass or equivalent)
- colour effects (B7 Colour)

AM[55]
A2.1 Rooflights (5)
A2.1.3 <u>Estimate of glazing required</u> (1)
Glazing area interacts with **choice of glazing material.**

AM[56]
A2.1 Rooflights (6)
A2.1.3 <u>Estimate of glazing required</u> (2)
(i) For a given daylight factor:
the glass area is inversely proportional to luminous transmittance;
(ii) For a given rate of heat loss through the glazing:
the glass area is inversely proportional to the U-value;
(iii) For a given daily mean rate of solar gain through the glazing:
the glass area is inversely proportional to the solar gain factor.

AM[57]
A2.1 Rooflights (7)
A2.1.3 <u>Estimate of glazing required</u> (3)
A2.1.3.1 Specify target average daylight factor (ADF)
A2.1.3.2 Estimate glazed area to provide target average daylight
A2.1.3.3 Check winter energy balance
A2.1.3.4 Check solar gain
A2.1.3.5 Reconcile thermal considerations

AM[58]
A2.1 Rooflights (8)
A2.1.3 Estimate of glazing required (4)
A2.1.3.1 <u>Specify target average daylight factor</u> (1)

- When ADF > 5% on the horizontal plane, an interior will look cheerfully daylit.
- When ADF < 2%, the interior will not be perceived as well-daylit and electric lighting may be in constant use.
- Irrespective of daylight factor, it is unlikely that full advantage of available daylight will taken unless lighting controls are appropriate.

AM[59]
A2.1 Rooflights (9)
A2.1.3 Estimate of glazing required (5)
A2.1.3.1 Specify target average daylight factor (2)

Consider:

- probable hours of use of building in relation to duration of usable daylight;
- illuminance to be satisfied for lighting design. (see CIBSE Code for Interior Lighting)

AM[60]
A2.1 Rooflights (10)
A2.1.3 Estimate of glazing required (6)
A2.1.3.1 Specify target average daylight factor (3)

The target ADF is derived in three stages:

(a) Decide the proportion of working year over which the illuminance is to be provided by daylight;
(b) Estimate the outdoor illuminance exceeded for this fraction of working year;
(c) Target average daylight factor:
{Specified indoor illuminance * 100 / Outdoor illuminance}

AM[61]
A2.1 Rooflights (11)
A2.1.3 Estimate of glazing required (7)
A2.1.3.2 Estimate glazed area to provide target ADF

For preliminary estimate, if clear glass is used, (Figure B1.1 and B1.2)

Net glazed area (approx.) = 5*(floor area) *(Target ADF) / θ

AM[62]
A2.1 Rooflights (12)
A2.1.3 Estimate of glazing required (8)
A2.1.3.3 Check winter energy balance (1)

Consider:

(a) Fabric heat loss through rooflight
(b) Ventilation heat loss
(c) Potentially beneficial solar gains through rooflights
(d) Height of space

AM[63]
A2.1 Rooflights (13)
A2.1.3 Estimate of glazing required (9)
A2.1.3.3 Check winter energy balance (2)
(a) Fabric heat loss through rooflight

This is proportional to U-value which depends on :

- exposure (sheltered, normal or severe) (CIBSE Guide Table A3.13)
- framing material (CIBSE Guide Table A3.14)
- air spaces in double or triple grazing (CIBSE Section A3)
- surface coating or gas filling for multiple glazing

AM[64]
A2.1 Rooflights (14)
A2.1.3 Estimate of glazing required (10)
A2.1.3.3 Check winter energy balance (3)
(b) Ventilation heat loss
Infiltration and ventilation heat loss:
proportional to the enclose volume of space.
(Some rooflight systems enclose a greater volume than others.)

AM[65]
A2.1 Rooflights (15)
A2.1.3 Estimate of glazing required (11)
A2.1.3.3 Check winter energy balance (4)
(c) Potentially beneficial solar gains through rooflights
Depends on:
- solar gain factor, which depends on the choice of glazing material;
- orientation and inclination of rooflight glazing;
- possible obstruction of winter sunlight by neighbouring roof lines.

AM[66]
A2.1 Rooflights (16)
A2.1.3 Estimate of glazing required (12)
A2.1.3.3 Check winter energy balance (5)
(d) Height of enclosed space
Any increase in the enclosed height due to rooflights increases the heat loss. (The extent of this effect will depend on the type of heating system)

AM[67]
A2.1 Rooflights (17)
A2.1.3 Estimate of glazing required (13)
A2.1.3.4 Check solar gain (1)
Broad decisions on **sunlight admission** should have been taken when the requirements were examined (A1.1.2) and **alternative rooflight profiles** were compared (A2.1.1).

AM[68]
A2.1 Rooflights (18)
A2.1.3 Estimate of glazing required (14)
A2.1.3. 4 Check solar gain (2)
The "daily mean rate of solar gain under heat wave conditions" is proportional to:
- Glazed area,
- Daily mean solar irradiance, which depends on
  - orientation and inclination of glazing
  - external obstruction (esp. by adjoining rooflights).
- Solar gain factor or shading coefficient, depending on:
  - the choice of glazing material
  - the choice of solar protection.

AM[69] None
AM[70] None

AM[71]
A2.1 Rooflights (19)
A2.1.3 Estimate of glazing required (15)
A2.1.3. 4 Check solar gain (3)
Solar protection
Surface tinted glass provides better solar protection than clear glass;
Body tinted glass provides better protection than surface tinted glass;
Reflective glass provides better protection than body tinted glass.

AM[72]
A2.1 Rooflights (20)
A2.1.3 Estimate of glazing required (16)
A2.1.3.4 Check solar gain (4)
Shading
Light shading provides better protection than dark;
External shading provides better protection than indoor shading;
Adjustable shading can provide higher daylight illuminance than fixed shading.

AM[73]
A2.1 Rooflights (21)
A2.1.3 Estimate of glazing required (17)
A2.1.3.5 Reconcile thermal considerations (1)
Reconcile **thermal consideration** (A2.1.3.3 and A2.1.3.4) with **daylighting demands** (A2.1.3.1 and A2.1.3.4), if necessary, by manipulating the area or other physical parameters of the rooflights.

AM[74]
A2.1 Rooflights (22)
A2.1.3 Estimate of glazing required (18)
A2.1.3.5 Reconcile thermal considerations (2)
It may be necessary to reconsider the **glazing material** (A2.1.2) or even the **rooflight profile** (A2.1.1).

AM[75]
A2.1 Rooflights (23)
A2.1.4 Establish rooflight position (1)

- If (rooflight spacing) / (height) ratios are excessive, the illumination will look patchy.
- The {spacing / height} ratio thus determines the minimum number or maximum spacing of rooflight runs.

AM[76]
A2.1 Rooflights (24)
A2.1.4 Establish rooflight position (2)
A2.1.4.1 Spacing / height ratios
The distance between any wall and the nearest rooflight should not exceed half the distance between adjacent rooflights. Also consider:

- feasible structural spans
- access to rooflights, for cleaning indoor and outdoor surfaces
- possible obstructive effects of overhead cranes and piped and ducked services.

AM[77] None

AM[78]
A2.1 Rooflights (25)
A.2.1.5 Establish window dimensions

Having established the rooflight profile (A2.1.3.5), the overall area of glazing required (A2.1.3.5) and the number of rooflights (A2.1.4), establish

- the **glazed area of each rooflight** and hence
- their **individual dimensions**.

AM[79]
A2.2 Side windows (1)

It is not always feasible to optimise window design separately for each individual room in a particular building. Designers should therefore identify, on each principal facade, one or two **key spaces**.

AM[80]
A2.2 Side windows (2)
A2.2.1 Specify window glazing materials
A2.2.2 Check depth of room
A2.2.3 Estimate area of window glazing required

AM[81]
A2.2 Side windows (3)
A2.2.1 Specify window glazing materials

Consider:

- luminous transmittance
- thermal transmittance (U-value)
- solar gain factor
- acoustic attenuation
- desire for privacy which may imply the permanent use of curtains or non-transparent glazing
- colour of glass.

AM[82]
A2.2 Side windows (4)
A2.2.2 Check depth of room (1)

If an interior is too deep, in relation to the height of the window head above the floor, it cannot be satisfactorily daylit. A room is too deep unless it satisfies both conditions, i.e.

- A2.2.2.1 No-sky line
- A2.2.2.2 Limiting depth.

AM[83]
A2.2 Side windows (5)
A2.2.2 Check depth of room (2)
A2.2.2.1 No-sky line

No significant part of the working plane shall lie beyond the no-sky line.

AM[84]
A2.2 Side windows (6)
A2.2.2 Check depth of room (3)
A2.2.2.2 Limiting depth (1) (windows on one wall only)
"$(l/w + l/h)$ shall not exceed 2/(1 - RB)"
where

l: the depth of the room from window to back wall,
w: the width of room, measured parallel to window,
h: the height of window head, above floor level,
RB: the area weighted average reflectance of the half of the interior remote from the window.

AM[85]
A2.2 Side windows (7)
A2.2.2 Check depth of room (4)
A2.2.2.2 Limiting depth (2)

- "If those conditions cannot be satisfied, the daylight will be unsatisfactory whatever the size of the window as the back of the room will always look gloomy compared with the space by the window."
- "Provided both conditions are satisfied, go to Stage A3."

AM[86]
A2.2 Side windows (8)
A2.2.3 Estimate area of window glazing required (1)
Glazing area interacts with choice of glazing material:

(a) For a given daylight factor: (See AM[55])
(b) For a given rate of heat loss: (See AM[55])
(c) For a given daily mean rate of solar gain: (See AM[56])
(d) For a given level of intrusive noise from outdoor:
an inverse relationship between the window area and its transmission coefficient. (Table B8.1)

AM[87]
A2.2 Side windows (9)
A2.2.3 Estimate area of window glazing required (2)
A2.2.3.1 Specify target ADF
See AM[58]

AM[88]
A2.2 Side windows (10)
A2.2.3 Estimate area of window glazing required (3)
A2.2.3.2 Estimate glazed area to provide target ADF
Glazed area will depend mainly on:

- luminous transmittance of glazing material
- extent of outdoor obstructions
- size and shape of interior
- reflectance of interior surface

To estimate glazed area use the equation in Part B1.1. (see AM[61])

AM[89]
A2.2 Side windows (11)
A2.2.3 Estimate area of window glazing required (4)
A2.2.3.3 Check winter energy balance (1)
Consider:

- fabric heat through windows and
- potentially beneficial solar gain through windows.

AM[90]
A2.2 Side windows (12)
A2.2.3 Estimate area of window glazing required (5)
A2.2.3.3 Check winter energy balance (2)
Ventilation heat loss is likely to be very important, but is ignored at this stage only because it is not regarded as a constraint on window area. (c.f. AM[64])

AM[91]
A2.2 Side windows (13)
A2.2.3 Estimate area of window glazing required (6)
A2.2.3.3 Check winter energy balance (3)
Fabric heat loss is proportional to U-value which depends on: (See AM[63])

AM[92]
A2.2 Side windows (14)
A2.2.3 Estimate area of window glazing required (7)
A2.2.3.3 Check winter energy balance (4)
"Potentially beneficial solar gain" depends on:

- solar gain factor, which depends on choice of glazing
- orientation of window
- outdoor obstructions to winter sunlight.

(c.f. AM[65]) (CIBSE Guide Table. A5.3, A5.4)

AM[93] (c.f. AM[68])
A2.2 Side windows (15)
A2.2.3 Estimate area of window glazing required (8)
A2.2.3.4 Check summer energy balance (1)
The daily mean rate of solar gain under heat wave conditions is proportional to:

- Window area,
- Daily mean solar irradiance, depending on:
  - orientation of window
  - outdoor obstructions,
- Solar gain factor, depending on:
  - choice of glazing material
  - choice of solar protection.

AM[94]
A2.2 Side windows (16)
A2.2.3 Estimate area of window glazing required (9)
A2.2.3.4 Check summer energy balance (2)
Solar protection: See AM[71], AM[72]

AM[95]
A2.2 Side windows (17)
A2.2.3 Estimate area of window glazing required (10)
A2.2.3.4 Check summer energy balance (3)

Consider alternatives for external solar screening:

(a) Fixed or movable: Movable screening allows better penetration of daylight on dull day.
(b) Vertical, horizontal or egg-crate.

AM[96]
A2.2 Side windows (18)
A2.2.3 Estimate area of window glazing required (11)
A2.2.3.4 Check summer energy balance (4)

Solar screening: in the UK,

- Vertical screening (e.g. fins) offers best protection for north-facing windows;
- Horizontal (e.g. a canopy) offers best protection for south-facing windows;
- Special planting of trees and shrubs can be most effective.

AM[97]
A2.2 Side windows (19)
A2.2.3 Estimate area of window glazing required (12)
A2.2.3.4 Check summer energy balance (5)

Solar screening:

East & west facing windows are difficult to protect from solar radiation without impairing natural lighting unless the screening is adjustable.

- Horizontal screening works better in summer than winter;
- Vertical screening works better in winter than summer.

AM[98]
A2.2 Side windows (20)
A2.2.3 Estimate area of window glazing required (13)
A2.2.3.5 Check noise transmission (1)

Site appraisal (Stage A1) should have indicated any likelihood of disturbance from traffic, aircraft, railway etc. (A1.2.5.1).

AM[99]
A2.2 Side windows (21)
A2.2.3 Estimate area of window glazing required (14)
A2.2.3.5 Check noise transmission (2)

External noise penetration may be reduced by following expediences, depending on the type of noise source:

(a) Use fixed windows.
(b) Design acoustic barriers.
(c) Use acoustic double windows (windows with wide internal air space).
(d) Use thick glass.
(e) Reduce window area.

AM[100]
A2.2 Side windows (22)
A2.2.3 Estimate area of window glazing required (15)
A2.2.3.6 Complete sizing procedure
Reconcile:

- thermal constraints (A2.2.3.3 and A2.2.3.4)
- acoustic constraints (A2.2.3.5) with daylighting requirements (A2.2.3.2),

if necessary, by manipulating the area or other physical parameters of the window. (c.f.AM[73])

AM[101]
Stage A3: Window shape and position
Having established the area of glazing for side windows, the next step is the arrangement of this glazing

- to achieve an acceptable **distribution of daylight,**
- to satisfy other requirements such as **view, privacy** and freedom from **glare**.

The key space identified in A2.2 will now be examined in greater detail.

AM[102]
Stage A3: Window shape and position
A3.1 Multilateral fenestration
A3.2 Daylight distribution
A3.3 Glare
A3.4 View
A3.5 Privacy
A3.6 Finalise shape and position of window

AM[103]
A3.1 Multilateral fenestration
Placing windows in more than one wall has potential advantages:

(a) The promote cross ventilation in naturally ventilated rooms.
(CIBSE Guide Table A8.4)
(b) They relieve dense shadows and harsh contrasts in side-lit rooms.
(c) They reduce the risk of sky glare by increasing window wall illuminance. It should be borne in mind, however, that the risk of overheating may be increased.

AM[104]
A3.2 Daylight distribution (1)

- The ADF should have been settled in A2.2.3.1 and A2.2.3.2.
- This **distribution of daylight factors** over the working plane depends on "how much sky is visible from different work stations".
- The **view** is more important than good daylighting, and window size can reflect this.

AM[105]

A3.2 Daylight distribution (2)

However, the following procedure will now optimise the **window shape** and **position** for interior lighting:

(a) Identify work stations or critical points at which good natural lighting should be ensured.
(If at this stage no such points are apparent, select points remote from the window.)

(b) Arrange the shape and position of windows **in relation to outdoor obstructions** so that the largest possible area of sky is visible from these critical points.

(c) If necessary, calculate the daylight factor at critical points using such standard methods as tables, 'pepperpot' diagram, BRS protractors and the Waldram diagram. (see B1 Daylight)

AM[106]

A3.3 Glare (1)

- Many complaints of 'glare' from windows refer to the thermal effects of solar radiation rather than to a visual impression.
- Three sources of window glare:
    - A3.3.1 Direct sunlight
    - A3.3.2 Reflected sunlight
    - A3.3.3 Skylight
- Most complaints are due to direct sunlight.

AM[107]

A3.3 Glare (2)

A3.3.1 Direct sunlight (1)

A direct view of the sun within 45° of the principal viewing direction will be intolerably glaring. This must be avoided.

- If necessary use blinds or curtains.
- Protection from direct solar radiation also gives visual protection from sunlight.

AM[108]

A3.3 Glare (3)

A3.3.1 Direct sunlight (2)

The best strategy for solar protection from sunlight is therefor **to concentrate on solving the thermal problems**. Analysis can use either the stereographic sunlight availability diagram, or a vertical sunpath perspective containing a 45° circle.

AM[109]

A3.3 Glare (4)

A3.3.2 Reflected sunlight

- Glare may be expected from **light-coloured, highly reflective sunlit surfaces** viewed from the interior of a deep office.
- The simplest remedy would be **an interior curtain** or **blind**.

AM[110]
A3.3 Glare (5)
A3.3.3 Skylight (1)

If the window faces an unobstructed horizon and no ground is visible to observers inside the room, glare discomfort will

- be virtually independent of window shape or size, and
- depend mainly on the luminance of sky through the window.

AM[111]
A3.3 Glare (6)
A3.3.3 Skylight (2)

Any view of external obstructions will 'buffer' sky glare. If this is an important consideration in design, **plan window shape and position so that observers see relatively more obstructions than sky**.

AM[112]
A3.3 Glare (7)
A3.3.3 Skylight (3)

Splayed reveals, windows in more than one wall, low-transmission glass and **high-reflectance walls** all reduce sky glare by diminishing the brightness difference between the window and the wall in which it is set.

AM[113]
A3.3 Glare (8)
A3.3.3 Skylight (4)

Diffusing or patterned glasses act as secondary light sources in that they become bright and glaring when light falls upon them.

AM[114]
A3.4 View (1)

The outside view often comprises three strata:

- sky
- buildings
- foreground.

Information is esp. concentrated in transitions between layers.

AM[115]
A3.4 View (2)

- For detailed analysis, one can draw, from a key viewpoint, a perspective of the window and of the scene beyond, or take a photograph at the correct viewing height.
- By redrawing the window outline, one can, if necessary, compare the effects of alternative window shapes and positions on the view.

AM[116]
A3.4 View (3)

Restricted window areas in deep offices:

- An optimum sill-to-head window height of 1.2 m.
- Satisfaction with the view increases as window width increases, but falls very sharply with any reduction in window height.

AM[117]

A3.5 Privacy

Three channels for visual intrusion may affect the position of windows:

- from interior to exterior,
- form exterior to interior, and
- from interior to another interior

AM[118]

A3.6 Finalise shape and position of window (1)

One can expect a conflict between the demands of:

- **daylight**: requiring maximum view of high-altitude sky (A3.2);
- **glare**: requiring excessive contrast to be reduced (A3.3);
- **view**: requiring access to skyline but little additional sky. Also access to foreground.

Reconcile these demands, preferably without returning to A2 to modify window area.

AM[119]

A3.6 Finalise shape and position of window (2)

Where a detailed study is required, use a gnomonic (perspective) projection, drawn from a key location indoors, to compare, for alternative window shapes and positions:

(a) Sky component of daylight factor,
(b) Solar orbits and sky area visible through window,
(c) Three strata of view: sky, buildings and foreground.

AM[120]

Stage A4: Integration of daylight and artificial light

Previous stages:

primarily concerned with lighting interior exclusively by windows and rooflights when the daylight is normally adequate (ADF > 5%).

However,

- Access to daylight may be obstructed,
- The area of glazing may have to be reduced below that necessary for effective daylighting, or
- The interior may be too deep to be daylit adequately from side windows.

Such conditions make it necessary to accept electric lighting during the hours of daylight.

Stage A4 concerns:

- the integration of natural and artificial lighting
- preventing waste of electricity.

Any automatic systems should be capable of being overridden by the occupants.

AM[121]
Stage A4: Integration of daylight and artificial light
A4.1 <u>Types of interior</u> (1)
(a) Interiors where ADF exceeds 5 % (A4.1.1)
(b) Roof-lit interiors where ADF < 2% (A4.1.2)
(c) Roof-lit or 'shallow' side-lit interiors whose ADF is between 2 and 5 % (A4.1.3; A 'shallow' side-lit room must satisfy both conditions of room depth (A2.2.2))
(d) A 'deep' side-lit room fails one or both the conditions of A2.2.2 (A4.1.4)

AM[122]
A4.1 <u>Types of interior</u> (2)
A4.1.1 ADF exceeds 5%
- Natural lighting levels should be adequate for most purposes during normal daylight hours.
- Plan electric lighting primarily for night-time use.
- Switches should be sensibly situated.
- Simple time controls could still be economically justified.

AM[123]
A4.1 <u>Types of interior</u> (3)
A4.1.2 Roof-lit interiors with ADF below 2%
- Supplementary electric lighting will be needed almost permanently.
- If automatic controls are adopted they may be designed to switch different luminaires at fixed steps of illuminance, or to dim them.

AM[124]
A4.1 <u>Types of interior</u> (4)
A4.1.3 ADF between 2 and 5%
- Electric lighting should be planned to take full advantage of available daylight (A4.2).
- Savings from automatic controls are particularly rewarding.
- Localised lighting may be advantageous, using daylight to provide ambient background lighting.

AM[125]
A4.1 <u>Types of interior</u> (5)
A4.1.4 Deep side-lit rooms
- Electric lighting must be carefully zoned, switching zones near windows being defined partly by daylight factor contours.
- 'Intermediate' colour lamps are generally recommended . (see B7 Colour)

AM[126]
A4.2 <u>Control systems for electric lighting</u> (1)
Almost all automatic controls require additional wiring.
Consider following alternatives, alone or in combination:
(a) Manual switching (A4.2.1)
(b) Time switching with manual override (A4.2.2)
(c) Automatic occupancy detection (A4.2.3)
(d) Photoelectric on/off (A4.2.4)
(e) Photoelectric dimming (A4.2.5)

AM[127]
A4.2 Control systems for electric lighting (2)
A4.2.1 Manual switching

- The number of switches should not be less than the number of rows of luminaires.
- Switch panels should be
  - conveniently sited, preferably in relation to daylight penetration,
  - clearly labelled, and
  - logically patterned.
- Consider pull-cord switches, low-voltage switching, remote switching, e.g. ultrasonic, infrared.

AM[128]
A4.2 Control systems for electric lighting (3)
A4.2.2 Time switching with manual override

Economic advantages in switching lights off during lunch breaks and at the end of the work day. (see B10 Lighting controls)

AM[129]
A4.2 Control systems for electric lighting (4)
A4.2.3 Automatic occupancy detection

Techniques still under development, including infrared, acoustic detection, miniature radio transmitters.

AM[130]
A4.2 Control systems for electric lighting (5)
A4.2.4 Photoelectric on/off control

- This system has greatest economic potential sited close to windows.
- Time delay is essential to prevent over-frequent operation.
- This system is more distracting than a dimmer-based system.
- Lamps with long restrike times need special consideration.

AM[131]
A4.2 Control systems for electric lighting (6)
A4.2.5 Photoelectric dimming

- More costly than on-off switching, but
- potentially more energy effective.
- Some lamp types become unstable on dimming.
- Circuit losses vary widely.

AM[132]
A4 Integration of daylight and artificial light
A4.3 Cost comparisons of alternative control systems

Energy savings depend on:

- design illuminance for electric lighting
- level of occupancy (BRE Digest 272)
- length of working day
- nature of control system
- daylight factor distribution
- outdoor climate.

(CIBSE Code for Interior Lighting Part 4)

BS8206 *Lighting for buildings*
Part 1. *Code of practice for artificial lighting*

BS8206_1[1]
4. Purpose and relationship with daylight (1)
4.1 Purpose

The main functions of artificial lighting:

(a) To enable the occupants to work and move about the building easily and safely
(b) To enable the occupants of the building to see the visual task with ease and accuracy;
(c) To enhance the appearance of the interior through the appropriate lighting of surfaces, colour and detail.

BS8206_1[2]
4. Purpose and relationship with daylight (2)
4.2 Relationship with daylight (1)

The potentials of daylighting and artificial lighting should be considered from the early stages in the design of a building. Decisions on the form of a building will have an important bearing on the roles of natural and artificial lighting. For instance, in deep buildings without rooflights, artificial lighting will be required continuously during occupation.

BS8206_1[3]
4. Purpose and relationship with daylight (3)
4.2 Relationship with daylight (2)

Even in buildings with rooms designed to be lit primarily by daylight, there will be times when artificial lighting has to be used to supplement the daylight. This possibility should be borne in mind when deciding on:

- the switching arrangement, and
- the appropriate colour appearance and colour rendering properties of lamps.

Where it is desired that artificial light should be **similar in colour to the daylight**, **lamps** with an intermediate or cold colour appearance will be suitable.

BS8206_1[4]
4. Purpose and relationship with daylight (4)
4.2 Relationship with daylight (3)

The **energy conserving potential of windows** is largely dependent upon:

- the magnitude and usefulness of the **solar gains**, and
- the extent to which the provision of **artificial light is controlled** in the presence of adequate natural light.

BS8206_1[5]
5. Visual environment (1)

Three functions of lighting (see 4.1):

(a) safety;
(b) task performance;
(c) appearance.

Most widely criterion:

- the **illuminance** provided on an appropriate plane, and
- uniformity.

BS8206_1[6]

5. Visual environment (2)

Illuminance provided on an appropriate plan

(a) Standard service illuminance (Table 1): Frequently, this plane is horizontal, but tasks in planes in other orientations do occur. The recommended illuminances apply to the appropriate plane and are **standard service illuminance.** ("standard": the recommended illuminances assume typical conditions for the applications being considered; "service": the illuminances recommended are averaged over the relevant area and over the life of the installation. Thus, the standard service illuminance is an average illuminance produced by the lighting installation on an appropriate plane in an area typical of the application.)

(b) Modification of the standard service illuminance to provide a **design service illuminance** (Table 2). When the situation is not typical, then the standard service illuminances can be modified according to the flow chart to provide a design service illuminance.

BS8206_1[7]

5. Visual environment (3)

- A **uniformity** criterion in terms of the ratio of minimum illuminance to maximum illuminance. An appropriate uniformity criterion on working area: 0.7 (equivalent to a min./average of 0.8).
- Another criterion applies to the uniformity of illuminance desirable, when working and non-working areas are adjacent. . In such situations, the illuminance on the surround area should not be less than 1/3 of that of the working area.

BS8206_1[8]

5. Visual environment (4)

The illuminances on other room surfaces and the reflectance of those surfaces strongly influence the appearance of the room and the comfort of the viewer as well as the ease of performance of the visual task.

Fig.1: The recommended ranges of room surface reflectance and illuminance ratios relative to the illuminance on the working area. (CIBSE Code for interior lighting)

Combinations of reflectance and illuminance ratios within the ranges given can produce a variety of appearances in an interior without creating discomfort.

BS8206_1[9]

5. Visual environment (5)

Discomfort glare"

The factors influencing the extent of discomfort glare:

(a) the luminance of the glare source;
(b) the luminance of the background;
(c) the size of the glare source;
(d) the position of the glare source relative to the line of sight.

The effect of all these factors has been combined to form "glare Index".

The glare index scale is such that higher values mean greater discomfort. Glare index can be evaluated from data produced by most manufacturers, or can be calculated by methods published by the CIBSE.

Disability Glare

It may cause a reduction in visibility of detail.

BS8206_1[10]
5. Visual environment (6)
"CCT" (Correlated Colour Temperature)
The colour of the light emitted by a near white source can be indicated by its correlated colour temperature (CCT). See Table 3:
The choice of an appropriate apparent colour of light source depends on
- the function of the room, and
- the impression it is required to create.

General rules to help with the selection of apparent colour are:
(1) for rooms lit to an illuminance of 300lx or less, a WARM or INTERMEDIATE apparent colour is preferred; COLD apparent colour lamps tending to give rooms a gloomy appearance at such illuminance.
(2) different apparent colour lamps should NOT be used haphazardly in the same room.

BS8206_1[11]
5. Visual environment (7)
"Colour rendering" (how accurate colour is judged)
The ability of a light source to render colours of surfaces accurately can be quantified by CIE general colour rendering index. For practical use they can be divided into a number of groups (see Table 4).
- Where work involving accurate colour judgement is to be done, light sources from groups 1A or 1B are necessary.

BS8206_1[12]
5. Visual environment (8)
"Veiling Reflection" & "Visible Flicker"
Two features of artificial lighting which can give rise to complaints, but not quantified by simple criteria.
Veiling reflections: the common solutions are either to use matt surfaces where possible, or change the angle of viewing and/or the surface from where the reflection occurs so that there is no longer a high luminance object at the mirror angle to the observer.
Visible flicker: Lamps which are producing visible flicker should be changed.

BS8206_1[13]
6. Energy considerations (1)
Following the recommendations will result in **the effective use of energy for artificial lighting**; but the designer should be alert to the possible interaction with:
- the other environmental factors and
- the consequences for the overall energy demand of the building.

BS8206_1[14]
6. Energy considerations (2)
Careful design is required to provide the recommended lighting conditions at minimum energy cost but being mindful that an installation can be expensive in terms of first costs and running costs.

BS8206_1[15]

6. Energy considerations (3)

The designer has to consider both:

- the details of the lighting installation and
- the contribution of that installation to the overall energy balance of the building.

BS8206_1[16]

6. Energy considerations (4)

Two factors which control the energy consumption :

(1) the POWER required to provide the lighting;
(2) the TIME for which that power is used.

BS8206_1[17]

6. Energy considerations (5)

The power is influenced by:

(i) the type of lighting system used;
(ii) the choice of light source;
(iii) the choice of luminaire.

BS8206_1[18]

6. Energy considerations (6)

(i) Choice of the type of "lighting system" & "power"

As a general rule, the installed load for local lighting is less than for localised lighting, which in turn is less than for general lighting. The choice is not simply a matter of installed power. Rather it is governed by organizational, technical and financial factors.

BS8206_1[19]

6. Energy considerations (7)

(ii) Choice of "lighting source" and "power"

Regardless of the type of lighting system chosen, the **choice of light source** is an important factor determining the power used to provided the artificial lighting. Different light sources convert electricity to light with different efficiencies. This efficiency is called **luminous efficacy** and is expressed in [lumens/Watt]. (see Table 5)

It should be noted that the discharged light sources, including fluorescent lamps, require a control circuit which increases the power requirements which will vary according to the type of circuit. For any specific application, chose:

- the light source with the highest luminous efficacy, and
- which is consistent with the other requirements of the application.

BS8206_1[20]

6. Energy considerations (8)

(iii) Choice of "luminaire" & "power"

Factors affecting the **choice of luminaire**:

(a) the light distribution they provide;
(b) the way they control glare;
(c) the environmental conditions encountered; or
(d) their appearance.

BS8206_1[21] 6. Energy considerations (9)

For the purpose of minimizing installed power, the only important characteristic is the **utilization factor** of the luminaire. This is the total proportion of the lamp light output which reaches the work plane. This is not a unique property of the luminaire itself, as it is also governed by the room in which the luminaire is placed. (A luminaire in a large room with high surface reflectance, will generally have a higher utilization factor than when placed in a small room with low surface reflectance.) Provided it complies with the other requirements, the luminaire with the highest utilization factor for the interior under consideration should be selected.

BS8206_1[22]

6. Energy considerations (10)

Other aspect of minimizing energy consumption: Controlling the hours of use of the installation (dealt with in the clause 8).

BS8206_1[23]

6. Energy considerations (11)

While the energy consumption of the lighting installation is of concern to the lighting designer, the building designer or his specialist advisor is concerned with the overall energy balance of the building. To assess this, he has to examine the interaction between:

- the pattern of building use;
- the building structure;
- the natural lighting; and
- the heating, cooling and ventilating system.

(Guidance for assessing energy balance of these aspects is given in the CIBSE Building energy code.)

BS8206_1[24]

7. Design process (1)

- Decisions about methods of lighting need to be taken early.
- The building designer should consult the lighting designer and others concerned at the conceptual stage.

BS8206_1[25]

7. Design process (2)

The first task is:

- Establish the visual task to be carried out within the building.
  (The possibility of future change in the use of the building should also be considered.)

BS8206_1[26]

7. Design process (3)

- The artificial lighting should be considered as part of the design of the interior environment as a whole.
- In addition to its relationship to daylighting, it may need to be related to the **thermal** and **acoustic requirements**.

BS8206_1[27]
7. Design process (4)
The details of the lighting design: (a)-(o)

BS8206_1[28]
8. Control of lighting (1)
8.1 General
Lighting controls should be arranged so that lighting load can be reduced

- in parts of buildings when no one or very few people are in occupation, and
- at time when daylight is providing a high illuminance over at least some of the working area. (see BRE Digest 272, 1983)

BS8206_1[29]
8. Control of lighting (2)
8.2 Manual controls
Controls should permit individual luminaires or rows of luminaires parallel to window walls to be controlled separately.

BS8206_1[30]
8. Control of lighting (3)
8.3 Central control
A remote operation electronic master control

- avoids the necessity for additional wiring to switches on walls, and
- can be used for overriding control when the room is unoccupied.
- all lights are off when the staff return after lunch break or the next morning.

BS8206_1[31]
8. Control of lighting (4)
8.4 Time controls
If the occupation of a building or any interior space effectively ceases at a fixed hour every working day, it may be worth installing a **time control** so that most of the lighting is switched off soon after this time and on non-working days.

BS8206_1[32]
8. Control of lighting (5)
8.5 Photoelectric controls (1)
8.5.1 General (1)
Photoelectric control can ensure that lighting cannot be switched on or remain on when the daylight provides the required illuminance by itself.

- The capital cost of these controls makes them usually only economic in large buildings with large daylit areas which are continually occupied during the day, e.g. offices, factories, schools and public circulation areas.

BS8206_1[32']
8. Control of lighting (5')
8.5 Photoelectric controls (2)
8.5.1 General (2)
In interiors where there is a large range of daylight factors, e.g. a fairly deep interior with two or more rows of lights running parallel to the window wall(s), it may be advantageous to use a separate controller for each row.

BS8206_1[33]
8. Control of lighting (6)
8.5 Photoelectric controls (3)
8.5.2 "On-off control"

An on-off switch controlled by the level of daylight inevitably produces a sudden change of illuminance on the working plane of roughly two to one if it is set to switch off the artificial lighting when daylight alone could provide the same illuminance. The occupants find it unsatisfactory.

BS8206_1[33']
8. Control of lighting (7)
8.5 Photoelectric controls (4)
8.5.3 "Top-up control"

Photoelectric dimming equipment can control the light output of lamps to provide sufficient illuminance to top-up daylight when it fails to reach the design level of the artificial lighting by itself.

- The artificial lighting is not fully on unless daylight falls to a negligible level.
- Such a system will use less energy than one which switches the lighting on fully for the whole time that the daylight is below the design illuminance, but
- it is more economic to arrange that some positive action has to be taken by the occupants to initiate the bringing-on action of the controller.

BS8206_1[33"]
8. Control of lighting (8)
8.5 Photoelectric controls (5)
8.5.4 "Savings"

The savings achievable by substituting photoelectric control for normal manual switching depend

- partly on the amount of daylighting entering the space,
- partly on the level of occupancy and
- partly on the use occupants make of the original manual switching arrangements.

BS8206_1[34]
8. Control of lighting (9)
8.6 Occupation sensors

These can be used to ensure that the lighting in a room is switched off when it is empty. Their cost may militate against their use in small spaces.

BS8206 *Lighting for buildings*
Part 2 *Code of practice for daylighting*

BS8206_2[1]
Foreword (1)
The standard:
- describes good practice in daylighting design, and
- presents criteria intended to enhance the well-being and satisfaction of people in buildings.

BS8206_2[2]
Foreword (2)
The aim of the standard to give guidance to architects, builders and others carrying out lighting design. It is recognized that lighting is only one of many matters that influence fenestration. These include other aspects of:
- environmental performance (such as noise, thermal equilibrium, control of energy use),
- fire hazards,
- constructional requirements;
- the external appearance;
- the surroundings of the site.

The best design for a building does not necessarily incorporate the ideal solution for any individual function. For this reason, careful judgement should be exercised when using the criteria given in the standard for other purposes, particularly town planning control.

BS8206_2[3]
1. Scope (1)
BS8206 Part 2 gives recommendations regarding design for daylight in buildings. It includes recommendations on the design of electric lighting when used in conjunction with daylight.

BS8206_2[4]
1. Scope (2)
Section 2 gives criteria for:
- the provision of view;
- the use of skylight & sunlight for general room lighting;
- the design of daylighting for task lighting.

Section 3 comprises recommendation for
- the design of supplementary electric lighting, and
- other related issues.

Section 4 gives methods of calculation.

BS8206_2[4']

2. Definitions

General: daylight / window / rooflight / transom / obstruction / no-sky line / working plane / room reference point / window reference point / supplementary electric lighting;
Sunlight: sunlight (see BS8206_2[18]) / possible sunlight hours / probable sunlight hours / solar altitude / solar azimuth;
Skylight: skylight (see BS8206_2[18]) / CIE standard overcast sky / daylight factor / average daylight factor / sky factor / sky component / externally reflected component / internally reflected component.

BS8206_2[5]

3. The contribution of daylight (1)

The use of windows:
(a) for view;
(b) to enhance the overall appearance of interiors using daylight: sunlight (the direct beam) and skylight (diffuse daylight);
(c) for illumination of visual tasks.

(b)&(c) may be fulfilled also by electric lighting. For many buildings, the best design uses daylighting and electric lighting together during daytime.

BS8206_2[6]

3. The contribution of daylight (2)

It is important to consider the **primary function** to be served by each window or rooflight in a building, because the criteria differ.

BS8206_2[7]

4. Windows and view (1)

4.1 Principle

Unless an activity requires the exclusion of daylight, a **view out-of-doors** should be provided irrespective of quality.

All occupants of a building should have the opportunity for the refreshment and relaxation afforded by a chance of scene and focus. Even limited view to the outside can be valuable.

BS8206_2[8]

4. Windows and view (2)

4.2 Analysis of view (1)

In planning the **position of windows**, the following factors are important:
(a) Most people prefer a **view** of a natural scene: trees, grass, plants and open space.
(b) A specific close view may be essential, particularly for security & supervision of the space around dwellings.
(c) There is often a need for **privacy**. This varies with the building type and with the expectations of the users. The view into a building should be considered when the view outwards is determined.

BS8206_2[9]
4. Windows and view (3)
<u>4.2 Analysis of view (2)</u>

Most unrestricted views have three 'layers':

(1) Upper (distant), being the sky and its boundary with the natural or man-made scene;
(2) Middle, being the natural or man-made objects themselves;
(3) Lower (close), being the groundscape forming foreground of the view.

Views including all three 'layers' are the most completely satisfying.

BS8206_2[10]
4.Windows and view (4)
<u>4.3 View in urban areas</u>

When only buildings, sky and street can be seen, it is especially desirable that the view be dynamic, i.e. including the activities of people outside and the changing weather, but even static view is usually better than none.

BS8206_2[11]
4. Windows and view (5)
<u>4.4 Size and proportion of windows</u> (1)

The **size and proportion of windows** should depend on:

- the type of view,
- the size of the internal space,
- the position & mobility of occupants.

BS8206_2[11']
4. Windows and view (6)
<u>4.4 Size and proportion of windows</u> (2)

Some circumstances may suggest a tall window which allows occupants anywhere to enjoy the full vertical span of the view. A narrow horizontal window will only offer a similar prospect to those close to it; a narrow vertical window is also restrictive yet will admit a deeper penetration of daylight.

BS8206_2[11"]
4. Windows and view (7)
<u>4.4 Size and proportion of windows</u> (3)

For a given area of window, the more exaggerated the horizontal or vertical proportions, the more restricted with the position of occupants who can experience the views.

BS8206_2[12]
4. Windows and view (8)
4.4 <u>Size and proportion of windows</u> (4)

- Unless a view of the sky is to be deliberately excluded, window heads should be above standing eye height.
- Sills, normally, should be below the eye level of people seated.
- Transoms should not obstruct significant parts of the view from normal standing or sitting position.

BS8206_2[12']
4. Windows and view (9)
4.4 Size and proportion of windows (5)
Special consideration should be given to window heights in rooms used by the elderly or the handicapped.

BS8206_2[13]
4. Windows and view (10)
4.4 Size and proportion of windows (6)
The most limited views occur in a deep room when windows are confined to one wall only.

BS8206_2[14]
4. Windows and view (11)
4.4 Size and proportion of windows (7)
Guidance on **minimum window area for a satisfactory view** when fenestration is restricted to one wall. (see Table 1) (Higher proportions are recommended.)

- When there are windows in 2 or more walls, the total area of glazing should not be less than the area that would be recommended if the windows were restricted to any one wall.

BS8206_2[15]
4. Windows and view (12)
4.4 Size and proportion of windows (8)
Table 1: Minimum window area for view
Note: Windows which are primarily designed for view may not provide adequate task illumination.

BS8206_2[16]
5. Daylight and room brightness(1)
5.1 General (1)
The value of daylight" goes beyond illumination of tasks:

- a daylit room varies in brightness with time;
- colours are rendered well;
- architectural form & surface texture can be enhanced by the direction of illumination;
- windows give information to the people in a building about their surroundings.

BS8206_2[17]
5. Daylight and room brightness (2)
5.1 General (2)
The user's perception (e.g. 'bright and well-lit', or 'gloomy') related to the brightness of all the visible surfaces. This overall luminance depends on:

- the quantity of light admitted;
- the reflectance of interior surface.

BS8206_2[18]
5. <u>Daylight and room brightness</u> (3)
Sunlight:

- part of solar radiation that reaches the earth's surface as parallel rays after selective attenuation by the atmosphere.
- gives patches of high illuminance and strong contrasts.

Skylight:

- part of solar radiation that reaches the earth's surface as a result of scattering in the atmosphere.
- adequate skylight ensures that there is not excessive contrast between one area of the room and another, between the interior and the view outside.

BS8206_2[19]
5. <u>Daylight and room brightness</u> (4)
If total glazed area cannot be made large enough for adequate general daylight, supplementary electric lighting is needed to enhance the general room brightness in addition to any need there may be for task illumination. (See Section 7.2)

BS8206_2[20]
5. Daylight and room brightness (5)
5.2 <u>Sunlight: principle</u> (1)
Sunlight should be admitted unless it is likely to cause thermal or visual discomfort to users, or deterioration of materials.

BS8206_2[21]
5. Daylight and room brightness (6)
5.2 <u>Sunlight: principle</u> (2)

- Controlled entry of sunlight is rarely unwelcome in U.K.
- Uncontrolled sunlight, however, is unacceptable in most type of building.
- Good control is particularly important in working interiors and other rooms where the occupants are unable to move around freely.

BS8206_2[22]
5. Daylight and room brightness (7)
5.2 <u>Sunlight: principle</u> (3)
Generally, sunlight should not fall on visual tasks or directly on people at work.

BS8206_2[22']
5. Daylight and room brightness (7')
5.2 <u>Sunlight: principle</u> (3')
It should, on the other hand, be used to enhance the overall brightness of interiors with patches of high illuminance.

BS8206_2[23]
5. Daylight and room brightness (8)
5.2 <u>Sunlight: principle</u> (4)
Considerations of sunlight should influence the **form of the building** from the early stages of design, because incorrect decisions about the **orientation of rooms** etc. may preclude the admission of sunlight or cause excessive **overshadowing** of surroundings.

BS8206_2[24]
5. Daylight and room brightness (9)
5.2 Sunlight: principle (5)
The **orientation of windows** should take into account:
- the **periods of occupancy**, and
- any **preferences for sunlight** at particular time of day.

BS8206_2[24']
5. Daylight and room brightness (9')
5.2 Sunlight: principle (5')
The provision of sunlight is important in dwellings, particularly during winter months. Sunlight is especially valued in habitable rooms used for long periods during the day and in buildings, such as those for the elderly, where the occupants have little direct contact with the outside.

BS8206_2[25]
5. Daylight and room brightness (10)
5.2 Sunlight: principle (6)
Note: Sunlight entering a room can have a significant effect on
- **thermal comfort**, and
- the **energy consumption** of the building.

In winter it can be an important contribution to the heating; but excessive solar gain causes serious discomfort and, in air-conditioned buildings, unnecessary use of energy in cooling.

BS8206_2[26]
5. Daylight and room brightness (11)
5.3 Sunlight duration (1)
- Interiors in which the occupants have a reasonable expectation of direct sunlight should receive at least 25% of probable sunlight hours.
- At least 5% of probable sunlight should be received during the winter months. (for Calculation see 12.2)

BS8206_2[27]
5. Daylight and room brightness (12)
5.3 Sunlight duration (2)
- The degree of satisfaction is related to the expectation of sunlight.
- It is the duration of sunlight in an interior, rather than its intensity or the size of sunny patch.

BS8206_2[28]
5. Daylight and room brightness (13)
5.3 Sunlight duration (3)
Note: In many buildings, discomfort and overheating may occur if the annual penetration of sunlight exceeds one third of probable sunlight hours."

BS8206_2[29]
5. Daylight and room brightness (14)
5.4 Skylight: principle (1)
The general illumination from skylight should be such that there is not excessive contrast between the interior and the view outside.

BS8206_2[29']
5.Daylight and room brightness (14')
5.4 Skylight: principle (2)
The interior of a room will appear gloomy
not only if the total quantity of light entering is too small, but also if its distribution is poor.

BS8206_2[29"]
5. Daylight and room brightness (14")
5.4 Skylight: principle (3)
If there is hight contrast between the surfaces surrounding windows (or rooflights) and the sky, there will be glare.

BS8206_2[30]
5. Daylight and room brightness (15)
5.5 Average Daylight Factor (1)
5.5.1 General

- Where a predominantly daylit appearance is wanted, the criteria given in 5.5.2 and 5.5.3 (interiors with / without supplementary electric lighting) should be adopted.
- The **Average Daylight Factor** is used as the measure of general illumination from skylight.

BS8206_2[31]
5. Daylight and room brightness (16)
5.5 Average Daylight Factor (2)
5.5.2 Interiors without supplementary electric lighting
If electric lighting is NOT normally to be used during daytime, the average daylight factor should be NOT less than 5%.

BS8206_2[32]
5. Daylight and room brightness (17)
5.5 Average Daylight Factor (3)
5.5.2 Interiors with supplementary electric lighting
If electric lighting is to be used throughout daytime, the average daylight factor should NOT less than 2%.

BS8206_2[33]
5. Daylight and room brightness (18)
5.6 Minimum values of average daylight factor in dwellings
Even if a predominantly daylit appearance is not required in dwellings, it is recommended that the average daylight factor be at least:

- 1% in bedrooms;
- 1.5% in living rooms;
- 2% in kitchen.

BS8206_2[33']
5. Daylight and room brightness (19)
5.7 Uniformity (1)
Surface reflectances and the disposition of glazing should be such that inter-reflected light in the space is strong and widespread.

BS8206_2[34]
5. Daylight and room brightness (20)
5.7 Uniformity (2)
Even if ADF exceeds 5% (see 5.5.2), supplementary electric lighting will be needed if:
- (a) a significant part of the working plane lies behind the no-sky line; or
- (b) in a room lit by windows in one wall only, the depth of the room is too large in comparison with the height & width of the windows.

BS8206_2[35]
5. Daylight and room brightness (21)
5.7 Uniformity (3)
- (a) In the case of **roof lights**, unsatisfactory variation in general lighting occurs when the distance between adjacent openings is large in comparison with the ceiling height.
- (b) The maximum acceptable ratio between rooflight spacing and ceiling height depends on the type of rooflight.

BS8206_2[35']
5. Daylight and room brightness (22)
5.7 Uniformity (4)
In interiors lit primarily by rooflights, the reflectances of the floor and ceiling should be as high as possible.

BS8206_2[36]
5. Daylight and room brightness (23)
5.8 Contrast between the interior and the view outside (1)
Glare from windows can arise from excessive contrast between the luminance of the visible sky and the luminance of the interior surfaces within the field of view. The window walls, the window reveals and the interior surfaces adjacent to rooflights should be of high **reflectance** (white or light-coloured). Walls generally should not be glossy.

BS8206_2[37]
5. Daylight and room brightness (24)
5.8 Contrast between the interior and the view outside (2)
Glare from the sky & bright external surface can be reduced by:
- (a) providing additional illumination;
- (b) reducing the luminance of the sky, with blinds etc. if adequate illumination can be provided by other sources (see BS8206_2[52]);
- (c) splaying window reveals.

BS8206_2[38]
5. Daylight and room brightness (25)
5.8 Contrast between the interior and the view outside (3)
The aim (of the measures to reduce glare from the sky etc. (see BS8206_2[37])) should be to achieve a subtle gradation of luminance from the darker parts of the room to the visible sky (see BS8206_2[52]).

BS8206_2[39]
5. Daylight and room brightness (26)
5.8 Contrast between the interior and the view outside (4)
Glare from direct sunlight or from sunlight reflected in glossy external surfaces should be controlled with **shading devices** (see Clause 8).

BS8206_2[39']
5. Daylight and room brightness (27)
5.8 Contrast between the interior and the view outside (5)
(Shading devices)
- The use of tinted glazing can affect colour perception.
- Care should be taken when safety or task performance requires good colour recognition.

BS8206_2[40]
6. Daylight for task lighting (1)
6.1 General (1)
The principle of lighting design using daylight are the same as those for electric lighting: it is necessary to
- achieve a given level of illumination;
- take account of the circumstances that determine its quality.

BS8206_2[41]
6. Daylight for task lighting (2)
6.1 General (2)
Daylight has the following characteristics as a task illuminance:
(a) A constant illuminance on the task cannot be maintained (changing weather, fluctuations by louvres etc.); in poor weather and at the ends of the working day, daylighting needs to be supplemented with electric lighting.
(b) The direction of light from windows, which act as large diffuse light sources to the side of a worker, gives good three-dimensional modelling. Rooflights, which give a modelling effect similar to that from large ceiling-mounted luminaires.;
(c) The spectral distribution varies during the course of a day, but colour rendering is usually considered to be excellent.

BS8206_2[42]
6. Daylight for task lighting (3)
6.2 Quantity of daylight (1)
6.2.1 The Task Illuminance
The task illuminance should be selected from Table 1 and Table 2 of BS8206 Part 1. (Procedures for calculating daylight illuminance are given in Clause 14)

BS8206_2[43]
6. Daylight for task lighting (4)
6.2 Quantity of daylight (2)
6.2.2 Uniformity (1)
Over the task area of an individual worker, the **uniformity** in illuminance should be such that the minimum illuminance should not fall below 0.8 of the average illuminance. (See BS8206 Part 1, Clause 5)

BS8206_2[43']
6. Daylight for task lighting (4')
6.2 Quantity of daylight (3)
6.2.2 Uniformity (2)
Where there are several working areas in an interior, the particular task illuminance should be attained on each, care being taken that the recommendations on uniformity in general room lighting are followed. (-> See 5.7)

BS8206_2[44]
6. Daylight for task lighting (5)
6.3 Quality of daylight (1)
6.3.1 General
Considerations described in "BS8206 Part 1" and "CIBSE *Code for interior lighting*" apply both to daylit interiors and to those with electric lighting.
There are two aspects of task daylighting which need particular attention: **Glare** and **Specular reflection**.

BS8206_2[44']
6. Daylight for task lighting (5')
6.3 Quality of daylight (1')
6.3.2 Glare (1)

- Distraction,
- A poor luminance balance between task and background,
- Discomfort glare

can all occur, if the visual task is viewed directly against the bright sky. Although a view outside should be provided, it is usually better if the glazing is at the side of workers.

BS8206_2[45]
Daylight for task lighting (6)
6.3 Quality of daylight (2)
6.3.2 Glare (2)
There is no standard procedure for calculating discomfort glare form skylight. ....
It should be reduced by ensuring that

- the sky is not in the intermediate field of vies with task;
- follow the recommendation given in 5.8 (contrast).

BS8206_2[46]
Daylight for task lighting (7)
6.3 Quality of daylight (3)
6.3.2 Glare (3)
Highly reflective sunlit external surfaces are more likely to add vitality to a scene.

BS8206_2[47]
Daylight for task lighting (8)
6.3 Quality of daylight (4)
6.3.2 Glare (4)

Glare from the sun, viewed directly or specularly reflected can be unacceptable in a working environment. If the sun or its mirrored image is likely to lie within 45° of the direction of view, then **shading devices** should be used (See Clause 8.1).

- Low transmittance glazing is unlikely to attenuate the beam sufficiently to eliminate glare;
- Diffusing glazing materials, in scattering the beam, may cause the window or rooflight itself to become an unacceptably bright source of light.

BS8206_2[48]
Daylight for task lighting (9)
6.3 Quality of daylight (5)
6.3.3 Specular reflection

The visibility of tasks can be seriously impaired by bright reflections of the sky in glossy surfaces. Special attention should be given to the avoidance of reflections of windows in VDU screen, chalkboards, and pictures in galleries, and it is preferable that these surfaces do not face a window directly.

BS8206_2[49]
7. Electric lighting used in conjunction with daylight (1)
7.1 Functions of supplementary electric lighting design

Electric lighting has two functions in a daylit building:

(a) To enhance the overall appearance of the room, by improving the distribution of illuminance and by reducing the luminance contrast between the interior and the view of outside.
(b) To achieve satisfactory illuminance on visual tasks.

BS8206_2[50] 7. Electric lighting used in conjunction with daylight (2)
7.2 Enhancement of room brightness (0)
7.2.1 Balance of daylight and electric light
7.2.2 Modelling
7.2.3 Contrast between interior and exterior
7.2.4 Illuminance from electric light
7.2.5 Colour appearance of lamps
7.2.6 Sequences of spaces

BS8206_2[51]
7. Electric lighting used in conjunction with daylight (3)
7.2 Enhancement of room brightness (1)
7.2.1 Balance of daylight and electric light

Daylight should appeared to the users to be dominant in the interior. This is normally achieved when the ADF is 2% or more, even though the horizontal illuminance from electric lighting may be greater than daylight illuminance.

BS8206_2[52]
7. Electric lighting used in conjunction with daylight (4)
7.2 Enhancement of room brightness (2)
7.2.1 <u>Balance of daylight and electric light</u>
The design of electric lighting should be such that occupants are aware of the "natural gradation" of daylight across interior surfaces and of changes in the light outside (see BS8206_2[37], [38]).

BS8206_2[53]
7. Electric lighting used in conjunction with daylight (5)
7.2 Enhancement of room brightness (3)
7.2.2 <u>Modelling</u>
The electric lighting should be designed with the daylighting to achieve optimum **modelling**,

- reinforcing the directionality where the natural illumination is too diffuse, and
- providing infill lighting where windows alone would give harsh modelling.

BS8206_2[54]
7. Electric lighting used in conjunction with daylight (6)
7.2 Enhancement of room brightness (4)
7.2.3 <u>Contrast between of interior and exterior</u>
Electric light is needed on these surfaces to reduce the luminance contrast with the view outside, when

- the general level of inter-reflected light is low, or
- the surfaces surrounding a window or rooflight are of low reflectance.

BS8206_2[55]
7. Electric lighting used in conjunction with daylight (7)
7.2 Enhancement of room brightness (5)
7.2.4 <u>Illuminance from electric light</u> (1)
The average working plane illuminance from electric lighting in the poorly daylit areas should be NOT less than 300 lx.

BS8206_2[56]
7. Electric lighting used in conjunction with daylight (8)
7.2 Enhancement of room brightness (6)
7.2.4 <u>Illuminance from electric light</u> (2)
The optimum balance between electric lighting and daylight occurs when the horizontal illuminance from electric lighting in areas remote from windows is approximately the same as the daylit illuminance 2 m from the windows.

BS8206_2[57]
7. Electric lighting used in conjunction with daylight (9)
7.2 Enhancement of room brightness (7)
7.2.5 Colour appearance of lamps

The sky varies in colour with time and in azimuth and altitude. .... Sunlight reflected into a room from vegetation or brightly coloured surfaces outside can have a noticeable hue and can affect the colour appearance of lamps.

Apparent discrepancies between the colour of electric light and of daylight may be reduced by:

(a) using lamps Intermediate class Correlated Colour Temperature;
(b) screening lamps from the view of occupants. (For this purpose, louvres with a cut-off at 45° to horizontal are preferable to any form of translucent diffuser.)

BS8206_2[58]
7. Electric lighting used in conjunction with daylight(10)
7.2 Enhancement of room brightness (8)
7.2.6 Sequence of spaces (1)

Adjacent rooms should NOT contrast harshly with each other in either brightness or the colour of the illuminance.

BS8206_2[59]
7. Electric lighting used in conjunction with daylight (9)
7.2 Enhancement of room brightness (9)
7.2.6 Sequence of spaces (2)

The building should be planned to avoid passing directly from a brilliantly sunlit space into one with a low level of combined lighting. A transitional space will help the eye to adapt in comfort from one to the other.

BS8206_2[60]
7. Electric lighting used in conjunction with daylight(11)
7.3 Task lighting
7.3.1 Illuminance
7.3.2 Direction and modelling
7.3.3 Colour

BS8206_2[61]
7. Electric lighting used in conjunction with daylight(12)
7.3 Task lighting (1)
7.3.1 Illuminance

- The total illuminance from daylight and electric light should satisfy the illuminance criteria for the visual task (see 6.2.1).
- A task should NOT be viewed against sky or a very bright area of the room. If this is unavoidable, its illuminance should be such that there is a satisfactory brightness-contrast between task and surroundings.

BS8206_2[62]
7. Electric lighting used in conjunction with daylight(13)
7.3 Task lighting (2)
7.3.2 Direction and modelling
Electric lightings should be designed so that good modelling assists task performance. (In case it's necessary to use electric lighting to increase the luminance of surfaces in shadow.)

BS8206_2[63]
7. Electric lighting used in conjunction with daylight(14)
7.3 Task lighting (3)
7.3.3 Colour
When discrimination of surface colour is essential for task performance, the choice of lamp should be that recommended for the task under entirely electric lighting.

BS8206_2[64]
7. Electric lighting used in conjunction with daylight(15)
7.4 Change in light at dusk
As dusk approaches, additional electric illumination is often needed, both
- to increase task illuminance near the windows and
- to improve the general brightness of the room,

but not for the purpose of reducing sky glare. Consideration should be given to the separation of daytime and night-time lighting. (Electric lighting control (clause 9))

BS8206_2[65]
8. Sunlight shading (1)
8.1 General
Admission of sunlight be controlled in all work spaces and other interiors where the thermal or visual consequences might lead to personal discomfort or cause materials to undergo unacceptable deterioration. The best control of sunlight penetration is achieved by careful planning of the orientation and disposition of rooms and their windows.

BS8206_2[66]
8. Sunlight shading (2)
8.1 General
All fenestration in position where sunlight could cause discomfort or damage should be provided with shading.

BS8206_2[67]
8. Sunlight shading (3)
8.1 General
For some interiors it is acceptable if sunlight is restricted during the warmer months by shading the apertures with elements such as balconies, overhanging roofs, or by fixed louvres or screens.
It may be possible to arrange **fixed shading devices** or install prismatic glazing so that daylight is redistributed to better effect, but all fixed devices reduce the skylight admitted and **glazed areas** may need to be increased.

BS8206_2[68]
8. Sunlight shading (4)
8.1 General
Low transmission 'solar' glazing

- will diminish light as well as **solar gain**; and
- is the best method of reducing summer cooling loads where large areas of glass are needed for view or appearance.

BS8206_2[69]
8. Sunlight shading (5)
8.1 General
Retractable and adjustable shading is often appropriate to the low solar altitude of the U.K. The system should be easily maintained and easily operated.

BS8206_2[69']
8. Sunlight shading (6)
8.1 General
Retractable and adjustable shading:
This is best achieved when shading systems are fitted internally, although Adjustable external systems should be robust, or restrict natural ventilation.

BS8206_2[70]
8. Sunlight shading (7)
8.1 General
This (i.e. easily maintained and operated) is best achieved when shading systems are **fitted internally**, although **shading devices on the outside** of the glazing are thermally more effective as heat from the intercepted radiation is more readily dissipated into the external air.

BS8206_2[71]
8. Sunlight shading (8)
8.1 General
Shading devices may interrupt the view and restrict natural ventilation.

BS8206_2[72]
8. Sunlight shading (9)
8.2 Overshadowing (1)
8.2.1 Overshadowing of a site by a proposed development
Examination of the duration and extent of site shadowing is recommended at the planning stage.

BS8206_2[73]
8. Sunlight shading (10)
8.2 Overshadowing (2)
8.2.2 Shadowing across site boundaries
In all development proposals,

- the lighting of the surrounding environment should be respected, and - an acceptable compromise presented between the requirements for sunlight of the new building and those of neighbouring buildings.

BS8206_2[73']
8. Sunlight shading (11)
8.2 Overshadowing (3)
8.2.3 Guidance
See the Building Research Establishment, BRE, Report "*Site layout planning for daylight and sunlight: a guide to good practice*" [1991]

BS8206_2[74]
9. Energy efficiency (1)
9.1 Energy consumption in lighting (1)
Within the U.K., lighting accounts for around 5% of the total primary energy consumed. However, in some type of buildings, such as office blocks, 30-60 % of the primary energy is used by lighting.

BS8206_2[75]
9. Energy efficiency (2)
9.1 Energy consumption in lighting (2)
The exploitation of daylight can do much to reduce the energy cost.

- In an RIBA case study, it was found that in general the shallow plan, daylit, naturally ventilated buildings had around half of the primary energy consumption of the "deep plan, air-conditioned buildings with extensive artificial lighting.
- Another BRE study indicated potential energy saving averaging 20-40 % in offices and factories, if daylighting is used effectively. To achieve such savings, not only should daylight be admitted to the building; but suitable controls should be installed to ensure the displacement of energy used for electric lighting.

BS8206_2[76]
9. Energy efficiency (3)
9.2 Window design and energy efficiency (1)
Windows can affect the energy balance of the building by:

- by conduction heat loss &
- by solar heat gain;
- by infiltration loss.

BS8206_2[77]
9. Energy efficiency (4)
9.2 Window design and energy efficiency (2)
Conduction heat loss:
Roughly proportional to window area; it can be reduced by using double or triple glazing with/without low emissive glass.

BS8206_2[78]
9. Energy efficiency (5)
9.2 Window design and energy efficiency (3)
Solar heat gain:

- Generally useful in winter when it reduces space heating requirement;
- In summer it can result in increased cooling load in air-conditioned building.
- The guidelines on the control of solar gain given in Clause 8 should be followed.

BS8206_2[79]
9. Energy efficiency (6)
9.2 Window design and energy efficiency (4)
If other factors remain unchanged, an increase in the window area will:

- increase solar gain;
- reduce artificial lighting use, if lighting controls are fitted; but
- conduction heat loss will increase.

The result is often that the **overall energy balance** in non-residential buildings does not vary greatly with **glazing area**.

BS8206_2[80] 9. Energy efficiency (7)
9.2 Window design and energy efficiency (5)
In general, optimum window areas are higher if double/triple glazed and if windows are south facing. Optimum window areas will be lower for single glazed and north facing windows, and if suitable lighting controls are not fitted.

BS8206_2[81]
9. Energy efficiency (8)
9.2 Window design and energy efficiency (6)
Optimum window areas: "the type of building" and "its occupancy pattern" play a part.

BS8206_2[82]
9. Energy efficiency (9)
9.2 Window design and energy efficiency (7)
In general, because of the small variation in building **energy consumption** with glazing area, energy criteria are often satisfied when window area are determined on the criteria of average daylight factor (see Clause 5).

BS8206_2[83]
9. Energy efficiency (10)
9.3 Passive solar design (1)
Daylighting and solar radiation are complementary in that daylighting can be used to reduce or eliminate casual heat gains form electric lighting, when solar gains are at their highest.

BS8206_2[83']
9. Energy efficiency (10')
9.3 Passive solar design (1')
The form, fabric and systems are arranged & integrated to maximize the benefits of ambient energy for heating, lighting and ventilation in order to reduce consumption of conventional fuels.

BS8206_2[84]
9. Energy efficiency (11)
9.3 Passive solar design (2)
In a domestic setting where lighting energy use is less important, the visual implications of passive solar design need to be recognised; Recommendations given in Section 2 should be followed.

BS8206_2[85]
9. Energy efficiency (12)
9.4 Lighting controls (1)

For daylight to make a real contribution to energy efficiency, appropriate lighting controls are essential. Four basic forms which can be linked to daylight:

(a) manual;
(b) timed switch off with optimal manual reset;
(c) photoelectric switch on/off;
(d) photoelectric dimming.
- Sensors which determine whether a space is occupied may be used.

(Part 1 of BS8206 gives recommendations and brief design guidance.)

BS6b[86]
9. Energy efficiency (13)
9.4 Lighting controls (2)

In a conventionally daylit commercial building, the choice of control can make 30-40 % difference to the resulting lighting use.

BS8206_2[87]
11. Statutory requirements affecting the provision of daylight
11.1 General
11.2 Rights of light
11.3 Building regulations

UNDERSTANDING BUILDINGS

Esmond Reid, Longman Scientific & Tecnical

UB[1]
Ch. 2. Enclosure
The 'small' house: Daylighting, views, ventilation (windows) (1)
<u>Daylighting (1)</u>
Daylighting ... naturally affects window design.
Window area needed relates to daylight needed.

- Room geometry and internal reflectance, and the anticipated tasks within, play a part;
- but, always remembering the thermal penalties that big windows incur.

UB[2]
Ch. 2. Enclosure
The 'small' house: Daylighting, views, ventilation (windows) (2)
<u>Daylighting (2)</u>
Window shape is also influenced by daylighting design.
High, narrow windows tend to admit more useful daylight than low, wide ones, principally because they offer more chance of the unobstructed sky source being 'seen' by the back of the room, where they improve lighting levels in consequence.

UB[3][4]
Ch. 2. Enclosure
The 'small' house: Daylighting, views, ventilation (windows) (3)
<u>Views out</u>
The desire to look out also influences shape, as well as suggesting
where windows should be located.
A low, horizontal window:

- tends to be claustrophobic if it cuts off the sky view, and
- offers a less representative view of what is outside than one with a vertical emphasis.
- Sills too high can block views out when people are seated; transoms can be awkwardly placed.
- A good view out can mean a good in, and need for greater privacy in rooms like bedrooms can dictate a higher sill.

UB[5]
Ch. 2. Enclosure
The 'small' house: Daylighting, views, ventilation (windows) (4)
<u>Ventilation</u>
Consideration in ventilation: The needs for cooling, and removing humidity, odours and bacteria, and supporting efficient combustion in fires and boilers.

- Summer ventilation may ask for as large an openable area as possible and, preferably, some of it should be at worktop level;
- The winter need is for a small opening and, preferably, at high level, where draughts will pass unnoticed;
- Any ventilation needs to be readily adjustable.

UB[6]
Ch. 2. Enclosure
The 'small' house: Daylighting, views, ventilation (windows) (5)
Sensible structure
Any opening will interrupt the structural continuity of a wall:
the narrow window makes more sense, a wider window having greater structural penalties, particularly with heavier wall constructions.

UB[7]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (1)
Influence on building shape (1)
Given that natural lighting is to be the day-time source, it inevitably has its influence on building shape. In the small house, there may be the chance to orientate the principal fenestration away from adjacent obstructions and - climate depending - towards or away from the maximum sky brightness.
(This is in addition to the considerations of thermal performance and view described in Chapter 2 Enclosure.)

UB[8]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (2)
Influence on building shape (2)
Large buildings must consider the effect of plan depth on light penetration (see Figure 5.4, page 143):
(a) adequate illumination a the back of a room;
(b) supplementary daylighting to the back (a rooflight);
(c) supplementary artificial lighting.

UB[9][10]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (3)(4)
Influence on building shape (3)
The question whether
- to go for a single-storey building allowing roof-light but entailing a large site, or
- mainly to dispense with daylighting in favour of having a more compact multi-storey building, better thermally and, possibly, cheaper to construct.

In practice, the decision will usually involve the experience of the lighting and environmental engineers, and cost consultants, as well as that of the architects.

UB[11]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (5)
Windows or rooflights?

Windows are the common daylighters because

- most rooms happen not to be directly under a roof,
- for view,
- they are well placed as ventilators.

The constraint is

- limited light penetration.

Rooflights can achieve a virtually even light distribution and, quantitatively, a more efficient daylighters, because

- they see the whole sky hemisphere whereas a window sees only half of it,
- rooflighting arrives more vertically and hence more intensely on the horizontal working plane.

But,

- the light-and-shade modelling tends to be duller, and
- thermal point is that rooflights make a building particularly vulnerable to overheating by the high summer sun.

UB[12]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (6)
Daylight design - the variables

The daylight reaching a given point inside is the sum of

- the direct sky component,
- the externally reflected component from adjacent buildings and other surfaces outside, and
- the internally reflected component.

The thing the designer usually needs to know is what geometry of room, and window or rooflight will ensure a specific minimum illumination.

UB[13]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (7)
Summary (1)

Daylight factor is influenced by

- external obstruction,
- window and room geometry, and
- internal reflection.

UB[14]
Ch. 5. Lighting
Daylighting
Designing for daylight quantity (8)
Summary (2)

Daylighting needs influence e.g.

- orientation,
- plan depth,
- sectional shape;

and pose choices, e,g,
- single-storey roof-lit and
- multi-storey side-lit.

UB[15]
Ch. 5. Lighting
Daylighting
Designing for daylight quality (1)

Avoiding glare is the single most crucial factor in good lighting quality. Lighting design distinguishes between disability glare and discomfort glare.

UB[16]
Ch. 5 Lighting
Daylighting - design for quality (2)
Disability glare

The case where the luminance contrast is enough actually to impair vision.
The area and/or brightness of the sky outside can be reduced by

- shades outside,
- tinted or reflective glazing, or
- translucent blinds inside.

Also, the brightness inside can be increased by using

- high surface reflectances or
- supplementary light sources, such as other windows, clerestories, rooflights, or artificial lighting.

UB[17]
Ch. 5 Lighting
Daylighting - design for quality (3)
Discomfort glare

It is where over-bright or ill-placed sources cause a nagging build-up of discomfort and destruction.

Window surrounds: The window wall has relatively low illuminance but this effect will be reduced somewhat if it is light-painted, reducing its contrast with the bright window aperture. The reveals around the window should be light-painted: the intermediate brightness helps visually by forming a 'buffer zone', grading the contrast between sky and interior.

Window shape: Tall windows are efficient quantitatively, since they show the interior more of the sky source, and the brighter part of the sky at that. But, qualitatively, they increase the risk of unacceptable glare.

Window shading: External shading is mostly associated with solar control, but in masking of the upper, brighter part of the sky, it can have a glare-control function also. Solar glasses have a related glare-control effect, and even the ordinarily glazed wall can have the upper band tinted against glare, above the level of the horizontal view out. The designer has to take account of the activity in a space, some activities being more than averagely glare-sensitive.

UB[18]
Ch. 5 Lighting
Daylighting - design for quality (4)
Glare control and modelling (1)

There are limits to useful glare control, however. A single, large window appears relatively brighter than several equipment, smaller ones, and more windows tend to mean greater diffusion. But, while the daylight inside a marquee or translucent sports bubble might be wholly diffuse, making for optimum conditions of adaptation, most people would eventually find the bland modelling and the very lack of contrast psychologically boring. UK domestic codes suggest a minimum of one hour in each of the principal rooms, with the house preferably oriented for morning sum in bedrooms and kitchen, and late sun in other living areas.

UB[19]
Ch. 5 Lighting
Daylighting - design for quality (5)
Glare control and modelling (2)

Strength of flow: The light 'flow' in a room causes contrasts in light and shade, sharpening our awareness of the shape of the room and the objects within it, their surface modelling and texture. The directional flow is strong with only one source such as a single window, and stronger still if the direct window component is very much greater than the internally-reflected component, i.e. where the reflectance of the room surface is low. Such arrangements would certainly cause glare.

Direction of flow: Strong down-lighting tends to model the human face rather curiously. Horizontal lighting models form rather curious too, and disfavours comfortable adaptation by bringing the source down into the visual field. The most people prefer - or a accustomed to - is slightly downward and from the side.

UB[20]
Ch. 5 Lighting
Daylighting - design for quality (6)
Illuminance distribution across a room - Uniformity ratio

The uniformity ration - the ratio of minimum to maximum illuminance - should be at least 0.7 for comfort. The distribution can be varied for special purposes. Higher illuminance on the work surface can aid vision and help focus concentration, always provided the strength and direction of the light flow is not such as to produced reflected glare off the task.

UB[21]
Ch. 5 Lighting
Artificial lighting (1)
Fitting the source to the building (1)

The suspended ceiling will usually have a module, co-ordinating the fittings and panels within the larger structural grid.

- The spacing of fittings is restricted by the need for lighting uniformity over the working plane.
- There may have to be ventilation to avoid overheating: simple convection slots in the fitting housing may be enough, but some positive mechanical extract is better, certainly over levels of 500 lux or so.

UB[22]
Ch. 5 Lighting
Artificial lighting (2)
Fitting the source to the building (2)

There has to be easy access for periodic cleaning of tubes and reflectors, and tubes to be replaced.

UB[23]
Ch. 5 Lighting
Artificial lighting (3)
Designing for artificial lighting quantity (1)

Three categories of lighting system:

- general lighting
- localised task lighting
- special lighting for architectural effect or display

UB[24]
Ch. 5 Lighting
Artificial lighting (4)
<u>Designing for artificial lighting quantity (2)</u>
Deciding on the illuminance required:

- See flow chart described in BS8206 Part 1;

Satisfying the requirement:

- Illuminance from a single source
- Average illuminance from multiple sources
- Uniformity ratio
- Refining the method

UB[25]
Ch. 5 Lighting
Artificial lighting (5)
<u>Designing for artificial lighting quantity (3)</u>
Summary

- Factors affecting lux from single source are intensity, offset angle, distance.
- Factors affecting average illuminance over space include number and output of fittings, maintenance factor, utilization factor, acknowledging losses in fittings and at room surfaces, and room area.

UB[26]
Ch. 5 Lighting
Artificial lighting (6)
<u>Designing for artificial lighting quantity (4)</u>
Fitting the source to the building
Fittings' spacing: no more than 1.5 times their height above the working plane. (1.25 times, if louvred and predominantly downward directional.)

UB[27]
Ch. 5 Lighting
Designing for artificial lighting quality (1)
<u>Colour appearance and rendering</u>
Artificial light sources vary in

- colour appearance, how the emitted light looks, and
- colour rendering, how it makes surrounding colours look.

Lighting intended to supplement daylight in an office needs daylight appearance for there to be an unobtrusive match, the diffuse overcast sky being the usual case to match.

UB[27']
Ch. 5 Lighting
Designing for artificial lighting quality (2)
<u>Glare</u>
See UB[29]

UB[27"]
Ch. 5 Lighting
Designing for artificial lighting quality (3)
Brightness of task to surroundings
Progressive grading asks for a task about three times brighter. (an ideal ratio between a book, desk top and room surface around is thought to be of the rough order 9:3:1.)
The need to achieve good overall lighting with reasonable economy in an office floor demands rather higher surface brightness, i.e. reflectances, than the ratio suggested.

UB[28]
Ch. 5 Lighting
Designing for artificial lighting quality (4)
Summary (1)
Choice of source depends on the relative need for
- accurate colour appearance and rendering, 'warmth', and/or
- efficiency.

UB[29]
Ch. 5 Lighting
Designing for artificial lighting quality (5)
Summary (2)
- Reflected glare is avoided by source/task geometry.
- Discomfort glare is mainly avoided by
  - fitting position and design,
  - good average room reflectance.
- Glare Index classifies maximum tolerable glare for various activities.

UB[30]
Ch. 5 Lighting
Designing for artificial lighting quality (6)
Summary (3)
BZ (British Zonal) Scale classifies fittings according to their distribution pattern.

UB[31]
Ch. 5 Lighting
Designing for artificial lighting quality (7)
Summary (4)
Visual ideal for business ratio (see UB[27"]) - mainly controlled by
- system choice (e.g. whether there are task lights or not)
- fitting design , and
- surface reflectance.

UB[32]
Ch. 5 Lighting
Designing for artificial lighting quality (8)
Two choices of system
General lighting is:
- centrally controllable,
- favoured where activities are interactive and mobile;

Task lighting:
- can be added where fixed tasks need high illuminance,
- adds personal control and visual interest.

UB[33]
Ch. 5 Lighting
Designing for artificial lighting quality (9)
Others
(1) The effect of room proportions
(2) Relative illuminance between adjacent area
(3) Window areas at night

UB[34]
Ch. 5 Lighting
Designing for artificial lighting quality (10)
(1) The effect of room proportions
Walls are significant quantitatively and qualitatively in a small, high room.
Ceiling is more significant in long, low room.

UB[35]
Ch. 5 Lighting
Designing for artificial lighting quality (11)
(2) Relative illuminance between adjacent area
Brightness contrast between areas must not cause discomfort in darker area nor be enough to outstrip the adaptation capability of passers through. e.g. The corridor can be a valuable intermediate 'buffer' between a dark ward and a bright treatment area, allowing staff's eyes more time to adopt.

UB[36]
Ch. 5 Lighting
Designing for artificial lighting quality (12)
(3) Window areas at night
Windows at night are screened not only against heat loss but to avoid light loss, specular reflections and reverse contrast. e.g. Curtains and blinds have obvious thermal benefits in cold weather but they have a role in lighting performance too.

UB[37]
Ch. 5 Lighting
Designing for artificial lighting quality (13)
Integrated day-time lighting (1)
Ideally, the lighting design should achieve an unobtrusive synthesis, the artificial supplement blending with the daylight, rather than rivalling it. So,

- the fluorescent need to be of the 'cool' daylight-matching type and, within this requirement,
- there may be finer adjustments, depending on whether the prevailing climate is predominantly clear or overcast, and on how far the glazing is north- or south-facing.

UB[38]
Ch. 5 Lighting
Designing for artificial lighting quality (14)
Integrated day-time lighting (2)
The illuminance of the mix must reduce gradually away from the windows, enough to simulate the daylight fall-off into the room but not so much that remote parts are inadequately lit (see 5.15 in page 157).

UB[39]
Ch. 5 Lighting
Designing for artificial lighting quality (15)
Integrated day-time lighting (3)

- The illumination appropriate to the room function must be a starting point, but, beyond this,
- integrated lighting can be taken as being needed anywhere the daylight factor on the working plane falls below 2%, or, if preferred, where the average daylight factor falls below 5%.

UB[40]
Ch. 5 Lighting
Designing for artificial lighting quality (16)
Integrated day-time lighting (4)

Also, excepting the very bright zone immediately adjacent to the windows, the mix should be so graded that the fall-off across the room results in an illuminance diversity no greater than 3:1 - effectively, a uniform ratio of at least 0.3.

UB[41]
Ch. 5 Lighting
Designing for artificial lighting quality (17)
Integrated day-time lighting (5)

The gradation of the mix across the room will further depend on the planning, asking for a logical fall-off away from side windows, a centre dip between opposite wall windows. A very simple installation might have discreet supplementary fittings, in addition to the ordinary fittings, for after dark.

UB[42]
Ch. 5 Lighting
Thermal implication of lighting (1)

- Windows increase heat loss in winter and, possibly, unwanted heat gain in summer.
- On the other hand, unless the plan is very deep, daylighting will be a valuable and perhaps the dominant lighting contribution to the day-time operation of a building.

UB[43]
Ch. 5 Lighting
Thermal implication of lighting (2)

Artificial lighting can bring double energy penalty,

- directly consuming electricity, and
- indirectly adding to the heat load the climate services have to dissipate.

There has to be a balance.

UB[44]
Ch. 5 Lighting
Thermal implication of lighting (3)

As a broad observation, artificial lighting levels have tended to reduce in recent years, partly because

- illuminance levels were originally set unnecessarily high, and
- more weight has come to be attached to the value of the daylight contribution in the reasonably shallow plan.

All this is notwithstanding the increasing efficiency and coolness of modern fluorescent types, and improved methods of useful heat recovery from artificial lighting installations.

UB[45]
Ch. 5 Lighting
Thermal implication of lighting (4)
The strategy for the deep-plan building (factory or office):

- artificial lighting prevails, with windows primarily for psychological need and comprising as little as 6% of the floor area.

UB[46]
Ch. 5 Lighting
Thermal implication of lighting (5)

- Where appropriate, fluorescent (or discharge) sources will be chosen rather than incandescent, and
- They will be the most efficient fluorescent consistent with the required colour appearance and rendering.
- The utilization factor will be improved by emphasising the downwards flux (which also helps glare-avoidance), and by having optimum surface reflectances.

UB[47]
Ch. 5 Lighting
Thermal implication of lighting (6)

- Localised lighting tends to be less efficient in terms of lumens out/watts put in, than the cool fluorescent in a general illuminating ceiling, especially if the former uses short fluorescent or incandescent.
- But, it can bring savings where high task illuminance is needed over selected areas only.

UB[48]
Ch. 5 Lighting
Thermal implication of lighting (7)
More efficient artificial lighting means less energy used: factors are

- lighting type (see UB[46])
- utilization factor (see UB[46])
- system type (see UB[47])
- control strategy:
    - allowing banks of lights to be switched off when not needed,
    - having timed automatic cut-outs, e.g. of office lights at night,
    - having photoelectric adjustment of integrated lighting.

BS8207 ***Code of practice for Energy Efficiency in Buildings***

BS7[1]
4 Energy requirement

The energy requirement should be established using a calculation procedure which takes into account at least the following factors:

(1) required environmental conditions and periods of use;
(2) climatic conditions;
(3) thermal transmittance of each part of the enclosure of the building;
(4) thermal response of the building's main constructional elements;
(5) rate of air change;
(6) effect of glazing on lighting use;
(7) effects of incidental gains (e.g. occupants, lighting, solar gain);
(8) effect of shading;
(9) effects of controls on the main energy-using services;
(10) efficiency of the equipment.

BS7[2]
Appendix B. Checklist (1)
Site selection

8. Check the required level of natural light; enclosed and shaded sites may require more use of artificial lighting.

BS7[3]
Appendix B. Checklist (2)
Building arrangement and shape (1)

2. Examine the possibilities of 'protecting' main areas of accommodation by adjacent lobbies, passages and similar spaces not necessarily heated to the same standard.

BS7[4]
Appendix B. Checklist (3)
Building arrangement and shape (2)

3. Use natural ventilation and daylight wherever possible (maximum recommended room depth 6 m for side-lit rooms in office buildings).

BS7[5]
Appendix B. Checklist (4)
Building arrangement and shape (3)

4. Ensure as far as possible that obstructions do not obscure daylight potential.

BS7[6]
Appendix B. Checklist (5)
Building arrangement and shape (4)

6. Consider orientation and its effect upon planning; summer solar gains are easier to control on the south facing sides of buildings and in larger rooms rather than smaller ones.

BS7[7]
Appendix B. Checklist (6)
Building fabric: *Structure*

1. Select a structure appropriate for the intended use
- thermally lightweight for intermittent use,
- thermally heavyweight (i.e. thermal admittance/thermal transmittance > 10) for continuous use and air-conditioned building.)

BS7[8]
Appendix B. Checklist (7)
Building fabric: *Windows and doors* (1)

1. Calculate window size to minimize heating and lighting loads. Take account of fortuitous gains, occupants, lighting, machines, etc.

BS7[9]
Appendix B. Checklist (8)
Building fabric: *Windows and doors* (2)

2. Avoid over provision of opening windows and minimize the use of opening windows having a high ratio of perimeter to glazed area;
   Consider the use of efficient closeable wall ventilators.

BS7[10]
Appendix B. Checklist (9)
Building fabric: *Windows and doors* (3)

3. Consider recessing windows to lessen their exposure and create shade, reducing summer solar gains yet allowing useful solar gains in winter. (Window overhangs and retractable external blinds also act in a similar way.)

BS7[11]
Appendix B. Checklist (10)
Building fabric: *Windows and doors* (4)

4. -
5. Consider double glazing for windows in continuously operated buildings.

BS7[12]
Appendix B. Checklist (11)
Building fabric: *Windows and doors* (5)

6. Consider shutters or curtains to reduce night-time heat losses.

BS7[13]
Appendix B. Checklist (12)
Building fabric: *Windows and doors* (6)

7. Consider rooflights to increase daylighting, but design avoid solar gain.

CIBSE *Code for Interior Lighting*

CIBSE[1]
4.4.1.4 Protection from glare and solar gain (1)
Fig 4.5 (a) A flowchart for selecting solar protection for windows (page 93).

CIBSE[2]
4.4.1.4 Protection from glare and solar gain (2)
Fig 4.5 (b) A flowchart for selecting solar protection for rooflights (page 94).

CIBSE[3]
4.4.3 Choice of lamp and luminaire
The choice of lamp will affect the range of luminaires available, and vice-versa. Therefore, one cannot be considered without reference to the other.

CIBSE[4]
4.4.3.1 Choice of lamp (page 96)

- Run-up time;
- Colour rendering properties;
- Apparent colour;
- Life and lumen maintenance characteristics;
- Stroboscopic effects; types of luminaires;
- Degree of light control and light output.

CIBSE[5]
4.4.3.2 Choice of luminaire (page 96-7)

- Physical condition, such as vibration, moisture, dust, ambient temperature, vandalism.
- Safety;
- Light distribution
- Utilization factor
- Luminaire reliability and life.

CIBSE[6]
4.4.2 Choice of electric lighting system (page 94-6)
(1) General lighting
(2) Localised system
(3) Local lighting
Is general, localised or local lighting most appropriate for the situation; does obstruction make some form of local lighting inevitable? (page 118)

CIBSE[7]
Layout (page 118)

- Is the layout of the installation consistent with the objectives and the physical constraints?
- Has allowance been made for the effects of obstruction by building structure, other services, machinery and furniture?
- Has the possibility of undesirable high luminance reflections from specular surfaces been considered; does the layout conform to the spacing height ratio criteria?

Other information sources

[Lecture_93]
A flow chart for selecting a suitable rooflight type
(See Figure B.8, Appendix B of this thesis)

[BRE]
Decision chart: selection of control strategy
(See Figure B.10, Appendix B of this thesis)

Appendix E

Appendix E

THE REFERENCE DIRECTORY AND THE CROSS-REFERENCES BETWEEN *DESIGN VARIABLES*

The building design process was described in terms of the relationships between *design variables* in Chapter 4. This Appendix E provides the materials which supplements Section 4.3. Appendix E.1 contains the list of the *design variables*, which were defined in Section 4.3.1. Appendix E.2 presents the reference directory which allows us to obtain the knowledge units associated with a particular relationship between the *design variables*. Appendix E.3 introduces the cross-references between the *design variables*.

E.1 *Design Variables*

In accordance with the rational description of building design work established in Section 4.2, three kinds of *design variables* were defined in Section 4.3.1. *Information variables* (In), *design decision variables* (Dd), and *performance variables* (Pe) together with *performance criteria* (Pc) are shown in Table E.1, Table E.2 and Table E.3, respectively.

Table E.1 *Information variables*, and the *design issues* which the variables are associate with. (Reproduced from Table 4.3)

Design issues	*Information variables*	
Design issue (1) General outline of requirements	In_01	Aim of the project
	In_02	Budget
	In_03	Time table
	In_04	Use of the building
	In_05	Accommodation
	In_06	Activities carried out
	In_07	Visual tasks
	In_08	Occupation patterns
Design issue (3) Context of the scheme	In_09	Boundaries
	In_10	Daylight availability
	In_11	Sunlight duration
	In_12	View
	In_13	Noise sources
	In_14	Physical pollution
	In_15	Ambient climate
	In_16	Local authorities and statutory regulations

Table E.2 *Design decision variables* (Dd) and their associated *design issues* (1) (Reproduced from Table 4.4)

Design issues	*Design decision variables*
Design issue (6) Design approach / priorities	Dd_01 Daylight priorities Dd_02 Sunshine priorities Dd_03 View priorities Dd_04 Ventilation priorities Dd_05 Noise insulation priorities
Design issue (7) Building's arrangement on the site	Dd_06 Position of the building on the site Dd_07 Orientation of the building
Design issue (8) Building form	Dd_08 Form of the building Dd_09 Use of rooflights Dd_10 Roof shape Dd_11 Glazing orientation and related glazing area Dd_12 Construction type
Design issue (9) Internal layout	Dd_13 Functional connections Dd_14 Accommodation plan Dd_15 Room depth
Design issue (10) Main ventilation methods	Dd_16 Use of natural ventilation Dd_17 Need for mechanical ventilation or air-conditioning

Table E.2 (continued) *Design decision variables* (Dd) and their associated *design issues* (2).

Design issues	*Design decision variables*
Design issue (11) Window design / fenestration	Dd_18 Rooflight profiles Dd_19 Glazing materials for rooflights Dd_20 Glazed area for rooflights Dd_21 Number and position of rooflights Dd_22 Area and dimension of individual rooflight Dd_23 Primary function of side windows Dd_24 Glazing material for side windows Dd_25 Glazed area for side windows Dd_26 Window shapes and positions Dd_27 Shading devices Dd_28 Reflectance of the interior
Design issue (12) Artificial lighting installation	Dd_29 Function of artificial lighting Dd_30 Lighting system Dd_31 Lamp types Dd_32 Lighting luminaires Dd_33 Arrangement of the luminaires Dd_34 Lighting control system

Table E.3 *Performance variables* (Pe) representing the performance characteristics of a design option, and their associated *performance criteria* (Pc), in relation to the *design aspects* (Da). (Reproduced from Table 4.5)

Design aspects	"**Pe**": *performance variables* representing the performance characteristics of a design option	"**Pc**": *performance criteria* associated with the *performance variables*
Da_0 *Energy efficiency*	Pe_01 Energy consumption	Pc_01 Energy targets
	Pe_02 Heat loss	none
Da_1 *Thermal comfort*	Pe_03 Solar gain	Pc_03 Thermal comfort level required
Da_2 *Air quality*	Pe_04 Ventilation performance	Pc_04 Air qualities required
Da_3 *Visual environment* *(lighting)*	Pe_05 Illuminance level on a working plane	Pc_05 Illuminance level required
	Pe_06 Uniformity of illuminance level	Pc_06 Uniformity required
	Pe_07 Average daylight factor (ADF)	Pc_07 Target ADF
	Pe_08 Colour properties	Pc_08 Colour properties required
	Pe_09 Appearance / modelling	none
	Pe_10 Glare and specular reflection	none
Da_4 *Visual environment* *(view)*	Pe_11 View	none
	Pe_12 Privacy	none
Da_5 *Acoustic consideration*	Pe_13 Noise level within the building	Pc_13 Noise insulation level required
Da_6 *Structural consideration*	Pe_14 Structure	none
Da_7 *External environment*	Pe_15 Overshadowing	none
Da_8 *Cost*	Pe_16 Cost	Pc_16 Cost range criteria (construction)
Da_9 *Aesthetics*	Pe_17 Aesthetics	none

E.2 The Matrices Describing the Relationships Between the *Design Variables*, and the Reference Directory

The relationships between the *design variables* were identified based upon the itemised knowledge units which are presented in Appendix D, and described in matrix forms, i.e. M_{InPe}, M_{InPc}, M_{InDd}, M_{DdPe}, M_{DdDd}, in Section 4.3.2. These matrices are also shown in Tables E.4, E.6, E.8, and E.10. Since the matrices indicate only the existence of the relationships between particular *design variables*, however, it is necessary to provide a means to obtain the itemised knowledge units which describe the relationships between the *design variables*. Therefore, a *reference directory* was developed in accordance with the matrix representation in Section 4.3.3. It is shown in Tables E.5, E.7, E.9, E.11 and E.13. The reference directory describes the association in terms of the "*address*" a particular relationship, and the "*reference numbers*" of the itemised knowledge units. Here, the *address* comprises the name of the matrix describing the relationships between particular *design variables*, such as M_{DdPe} for those between *design decision variables* and *performance variables*, and the position of an element within the matrix which has a value of "1", so that a particular pair of *design variables* can be specified. The *reference numbers* are, meanwhile, used to specify the itemised knowledge units which are associated with the particular relationship. Within the reference directory, the addresses of the relationships between *design variables* appear in the left column, whereas the reference numbers are shown in the other five columns depending upon the source of the itemised knowledge. (For the abbreviations see Appendix D.) Within the reference directory, the reference numbers in bold indicate the units of knowledge which are considered to contain the comprehensive information regarding to the relationships. The reference directory is presented, along with the matrices describing the relationships between the *design variables*, below.

Table E.4 M_{InPe}: Matrix representing the relationships between *information variables* (In) and *performance variables* (Pe)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Pe01	Pe02	Pe03	Pe04	Pe05	Pe06	Pe07	Pe08	Pe09	Pe10	Pe11	Pe12	Pe13	Pe14	Pe15	Pe16	Pe17
1	In_01																	
2	In_02																	
3	In_03																	
4	In_04	1																
5	In_05							1										
6	In_06	1									1							
7	In_07																	
8	In_08	1																
9	In_09												1			1		
10	In_10		1	1				1								1		
11	In_11		1	1														
12	In_12											1						
13	In_13													1				
14	In_14																	
15	In_15	1	1															
16	In_16																	

Table E.5 Reference directory regarding the relationships between *information variables* (In) and *performance variables* (Pe)

Address		Sources of the itemised knowledge units				
MInPe		AM	BS8206-1	BS8206-2	U.B.	Others
4	1	-	23	-	-	-
5	7	-	-	33	-	-
6	1	-	-	-	-	BS7[1]
6	10	-	-	48	-	-
8	1	-	**23**	-	-	BS7[1]
9	2	26	-	-	-	-
9	15	-	-	**72, 73**	-	-
10	2	**65, 92**	-	-	-	-
10	3	65, 92, 93	-	-	-	-
10	7	-	-	-	13	-
10	15	-	-	72	-	-
11	2	**65, 92**	-	-	-	-
11	3	**65, 92**	-	26, 27	-	-
12	11	-	-	7	-	-
13	13	98	-	-	-	-
15	1	132	-	-	-	**BS7[1]**
15	2	63, 91, 132	-	-	-	-

Table E.6 M_{InPc}: Matrix representing the relationships between *information variables* (In) and *performance criteria* (Pc)

		1	2	3	4	5	6	7	8	9
		Pc01	Pc03	Pc04	Pc05	Pc06	Pc07	Pc08	Pc13	Pc16
1	In_01	1								
2	In_02	1								1
3	In_03									
4	In_04									
5	In_05						1			
6	In_06		1	1	1	1		1	1	
7	In_07				1	1		1		
8	In_08						1			
9	In_09									
10	In_10						1			
11	In_11									
12	In_12									
13	In_13									
14	In_14									
15	In_15									
16	In_16									

Table E.7 Reference directory regarding the relationships between *information variables* (In) and *performance criteria* (Pc)

Address		Sources of the itemised knowledge units				
MinPc		AM	BS8206-1	BS8206-2	U.B.	Others
1	1	-	-	-	-	BS7[1]
2	1	-	14	-	-	-
2	9	-	14	-	-	-
5	6	-	-	33	-	-
6	4	-	6	-	-	-
6	5	-	**7**	**43, 43'**	-	-
6	7	-	11	-	-	-
6	8	30	-	-	-	-
7	4	-	**6**	42	39	-
7	5	-	7	43	-	-
7	7	-	11	-	-	-
8	6	**59**, 60	-	-	-	-
10	6	60	-	-	-	-

Table E.8 M_{InDd}: Matrix representing the relationships between *information variables* (In) and *design decision variables* (Dd)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		d01	d02	d03	d04	d05	d06	d07	d08	d09	d10	d11	d12	d13	d14	d15	d16	d17	d18	d19	d20	d21	d22	d23	d24	d25	d26	d27	d28	d29	d30	d31	d32	d33	d34
1	In_01	1		1	1																														
2	In_02																																		
3	In_03																																		
4	In_04		1										1																						
5	In_05													1	1																				
6	In_06	1	1	1		1						1		1					1				1			1	1				1	1	1		
7	In_07	1																			1					1					1	1			
8	In_08	1										1	1										1				1								1
9	In_09	1	1				1	1	1															1		1	1								
10	In_10	1	1				1	1	1			1				1					1	1	1	1		1	1			1					
11	In_11		1																									1							
12	In_12			1																						1	1								
13	In_13	1	1		1	1	1	1	1			1					1	1	1						1	1	1								
14	In_14	1	1	1	1		1	1	1	1		1					1	1	1		1				1	1	1								
15	In_15	1	1		1		1	1	1			1					1		1		1				1	1						1			
16	In_16						1	1	1			1									1					1									

Table E.9 Reference directory regarding the relationships between *information variables* (In) and *design decision variables* (Dd) (1/2)

Address		Sources of the itemised knowledge units				
MInDd		AM	BS8206-1	BS8206-2	U.B.	Others
1	1	-	-	-	-	BS7[6]
1	3	-	-	7	-	-
1	4	-	-	-	-	BS7[4]
4	2	**15**	-	**24'**	-	-
4	12	-	-	-	-	BS7[1]
5	13	-	-	-	-	BS7[6]
5	14	-	-	-	-	BS7[3]
6	1	8	-	-	-	-
6	2	15, **67**	-	**24'**	-	-
6	3	**16**	-	7	-	-
6	5	30	-	-	-	-
6	11	-	-	24	-	-
6	13	-	-	-	-	BS7[3]
6	18	**51, 52, 53**	-	-	-	-
6	22	-	-	24	-	-
6	25	-	-	11	-	-
6	26	**105**	-	**11, 12'**, 24	-	-
6	30	-	-	-	32	-
6	31	-	-	-	-	CIBSE[4]
6	32	-	-	-	-	CIBSE[5]
7	1	8	-	-	-	-
7	20	-	-	-	1	-
7	25	-	-	-	1	-
7	30	-	-	-	32	-
7	31	-	-	-	-	CIBSE[4]
8	1	8	-	-	-	-
8	11	-	-	24	-	-
8	12	-	-	-	-	BS7[1]
8	22	-	-	24	-	-
8	26	-	-	24	-	-
8	34	**Table B10.2**	**28**, 31	64	-	-
9	1	20	-	-	-	-
9	2	20	-	-	-	-
9	6	**20**, 23, 25, 27	-	-	-	-
9	7	**20**, 23, 25	-	-	-	-
9	8	**20**, 23, 25	-	-	-	-
9	23	20	-	-	-	-
9	25	20	-	-	-	-
9	26	20	-	-	-	-
10	1	**8**, 9	-	-	-	-
10	2	13	-	-	-	-
10	6	20, 25, 27, **37**	-	-	-	-
10	7	20, 25, **37**	-	-	-	-
10	8	20, 25, **37**	-	-	-	-
10	11	20, **37**	-	-	-	-
10	15	82	-	-	-	-
10	20	20, **36**	-	-	-	-
10	21	20, **36**	-	-	-	-
10	22	20, **36**	-	-	-	-
10	23	**20**	-	2	-	-
10	25	20, **36, 88**	-	-	-	-
10	26	20, **36, 105**	-	-	-	-
10	29	**20**	-	-	-	**BS7[2]**
11	2	13	-	**26, 27**	-	-
11	27	-	-	2, **28**	-	-

Table E.9 Reference directory regarding the relationships between *information variables* (In) and *design decision variables* (Dd) (2/2)

Address		Sources of the itemised knowledge units				
MInDd		AM	BS8206-1	BS8206-2	U.B.	Others
12	3	**16**	-	7, 10	-	-
12	25	-	-	11	-	-
12	26	-	-	11	-	-
13	1	20	-	-	-	-
13	2	20	-	-	-	-
13	4	18'	-	-	-	-
13	5	**19, 30'**	-	-	-	-
13	6	20	-	-	-	-
13	7	20	-	-	-	-
13	8	20	-	-	-	-
13	11	28	-	-	-	-
13	16	18', **28**	-	-	-	-
13	17	28	-	-	-	-
13	18	28	-	-	-	-
13	24	18'	-	-	-	-
13	25	28	-	-	-	-
13	26	28	-	-	-	-
14	1	20	-	-	-	-
14	2	20	-	-	-	-
14	3	31	-	-	-	-
14	4	31	-	-	-	-
14	6	20	-	-	-	-
14	7	20	-	-	-	-
14	8	29	-	-	-	-
14	9	31"	-	-	-	-
14	11	**28**, 29	-	-	-	-
14	16	28	-	-	-	-
14	17	**28, 31**	-	-	-	-
14	18	31'	-	-	-	-
14	20	31'	-	-	-	-
14	24	29	-	-	-	-
14	25	28	-	-	-	-
14	26	28	-	-	-	-
15	1	**20, 29'**	-	-	-	-
15	2	20	-	-	-	-
15	4	32	-	-	-	-
15	6	**20, 33**	-	-	-	-
15	7	**20, 33**	-	-	-	-
15	8	**20, 33**	-	-	-	-
15	11	32	-	-	-	-
15	16	32	-	-	-	-
15	18	34	-	-	-	-
15	20	32	-	-	-	-
15	24	32	-	-	-	-
15	25	32	-	-	-	-
15	31	-	-	-	37	-
16	6	**21, 23**	-	-	-	-
16	7	23	-	-	-	-
16	8	**21, 23**	-	-	-	-
16	11	22	-	-	-	-
16	20	22	-	-	-	-
16	25	22	-	-	-	-

Table E.10 M_{DdPe}: Matrix representing the relationships between *design decision variables* (Dd) and *performance variables* (Pe)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Pe01	Pe02	Pe03	Pe04	Pe05	Pe06	Pe07	Pe08	Pe09	Pe10	Pe11	Pe12	Pe13	Pe14	Pe15	Pe16	Pe17
1	Dd_01	1	1	1			1	1	1	1	1	1						
2	Dd_02	1		1							1							
3	Dd_03											1	1					
4	Dd_04																	
5	Dd_05																	
6	Dd_06			1				1				1	1			1		
7	Dd_07			1				1				1	1			1		
8	Dd_08	1	1	1				1					1			1	1	1
9	Dd_09		1	1			1			1								
10	Dd_10			1														
11	Dd_11	1	1	1				1			1		1					
12	Dd_12	1	1															
13	Dd_13					1												
14	Dd_14			1		1		1	1	1								
15	Dd_15							1				1						
16	Dd_16	1	1															
17	Dd_17	1	1															
18	Dd_18		1	1				1		1								
19	Dd_19		1	1				1	1		1							
20	Dd_20	1	1	1				1										
21	Dd_21						1				1				1			
22	Dd_22		1	1			1	1			1							
23	Dd_23									1								1
24	Dd_24		1	1				1	1		1			1				1
25	Dd_25	1	1	1				1				1		1				1
26	Dd_26		1	1	1		1	1		1	1	1	1		1			1
27	Dd_27	1	1	1	1		1	1	1		1	1						1
28	Dd_28					1	1	1			1							1
29	Dd_29	1				1	1	1	1	1	1							
30	Dd_30	1				1	1										1	
31	Dd_31	1							1		1						1	
32	Dd_32	1									1						1	
33	Dd_33	1					1			1	1						1	
34	Dd_34	1					1										1	

Table E.11 Reference directory regarding the relationships between *design decision variables* (Dd) and *performance variables* (Pe) (1/3)

Address		Sources of the itemised knowledge units				
MDdPe		AM	BS8206-1	BS8206-2	U.B.	Others
1	1	29'	-	**75**	-	-
1	2	29'	-	-	7, **42**	-
1	3	42, 44	-	-	7, **42**	-
1	6	-	-	**29**, 43	-	-
1	7	-	-	**30, 31, 32**	-	-
1	8	-	-	**16, 41**	-	-
1	9	-	-	**16, 41**	-	-
1	10	-	-	29	-	-
1	11	-	-	-	7	-
2	1	-	-	25	-	-
2	3	-	-	**20**, 25	-	-
2	10	-	-	20	-	-
3	11	-	-	7	-	-
3	12	**26**	-	8	-	-
6	3	-	-	23	-	-
6	7	**35**, 37	-	-	-	BS7[5]
6	11	-	-	7	-	-
6	12	23, **26**	-	-	-	-
6	15	23, 24, 25, 35, **39, 40, 41**	-	72, 73, 73'	-	-
7	3	**17**	-	**23**	-	**BS7[6]**
7	7	**35**, 37	-	-	-	-
7	11	**17**	-	**7**	-	-
7	12	26	-	-	-	-
7	15	23, 24, 25, 35, **39, 40, 41**	-	72, 73, 73'	-	-
8	1	29'	-	**75**	-	-
8	2	**62, 66**	-	-	-	-
8	3	-	-	23	-	-
8	7	**35**, 37	-	-	-	-
8	12	23	-	-	-	-
8	15	23, 24, 25, 35, **39, 40, 41**	-	72, 73, 73'	-	-
8	16	-	-	-	9	-
8	17	-	-	-	9	-
9	2	62	-	-	-	-
9	3	-	-	-	11	BS7[13]
9	6	-	-	-	11	-
9	9	-	-	-	11	-
10	3	68	-	-	-	-
11	1	**43**	-	82	-	-
11	2	**43**, 100	-	-	-	-
11	3	**43**, 92, 93, 100	-	28	-	-
11	7	**35, 37**	-	-	13	-
11	10	-	-	65	-	-
11	12	26	-	-	-	-
12	1	-	23	-	-	BS7[7]
12	2	-	-	-	-	BS7[7]
13	5	-	-	58	35	-
14	3	-	-	65	-	-
14	5	-	-	**58, 59**	-	-
14	7	35	-	-	-	-
14	8	-	-	**58, 59**	-	-
14	9	-	-	-	18	-

Table E.11 Reference directory regarding the relationships between *design decision variables* (Dd) and *performance variables* (Pe) (2/3)

Address		Sources of the itemised knowledge units				
MDdPe		AM	BS8206-1	BS8206-2	U.B.	Others
15	7	-	-	-	8	-
15	11	-	-	13	-	-
16	1	-	23	25, 75	-	**BS7[1]**
16	2	62, 64, **90**	-	-	-	-
17	1	-	**23**	25	-	BS7[1]
17	2	62, **64**, 90	-	-	-	-
18	2	**66, 73, 74**	-	-	-	-
18	3	**51, 52, 53**, 73, 74	-	-	-	Lecture_93
18	7	**51**, 73	-	-	-	-
18	9	-	-	-	-	Lecture_93
19	2	**54**, 63, **73, 74**	-	77	-	-
19	3	54, 65, 68, 71, 73, 74	-	68	-	-
19	7	**54**, 73	-	-	-	-
19	8	54	-	39'	-	-
19	10	113	-	-	16	-
20	1	-	-	**79, 82**	-	-
20	2	56, **62, 63**, 73	-	**77**, 79	1	-
20	3	56, **68**, 73	-	**79**	1	-
20	7	56, **61**, 73	-	-	-	-
21	6	**75, 76**	-	**35**	-	-
21	10	-	-	29	-	-
21	14	76	-	-	-	-
22	2	**65**, 73	-	80	-	-
22	3	65, **68**, 73	-	**65**	-	-
22	6	-	-	29'	-	-
22	7	73	-	-	-	-
22	10	-	-	65	-	-
23	9	46	-	-	-	-
23	17	-	-	2	-	-
24	2	**81, 89, 91, 92**	-	**77**	-	-
24	3	81, 89, 92, 93, 94,108	-	68	-	-
24	7	**81, 86**	-	68	-	-
24	8	**81**	-	**39'**	-	-
24	10	107, 108, **112, 113**	-	**47**	16	-
24	13	86, **99**	-	2	-	-
24	17	-	-	**2**	-	-
25	1	-	-	**79, 80, 81, 82**	-	-
25	2	89, 91, 100	-	**77**, 79	1	-
25	3	89, **93**, 100	-	79	1	-
25	7	**61, 88, 100**	-	19	-	-
25	11	-	-	**14, 15**	-	-
25	13	**99**, 100	-	-	-	-
25	17	-	-	**2**	-	-
26	2	92	-	-	-	-
26	3	93	-	2, **65**	-	-
26	4	**103**	-	-	5	-
26	6	101, **103, 104**, 118, 119	-	**33', 38**	2	-
26	7	-	-	11'	**2**	-
26	9	**103**	-	41	-	-
26	10	101, 103, 107, **110, 111, 112**	-	29, **37, 38**, 44, 44', 65	17	-
26	11	101, **115, 116**, 118	-	8, **11', 11", 12, 13**	3, 4	-
26	12	26, 101, 117	-	**8**	4	-
26	14	-	-	-	6	-
26	17	-	-	2	-	-

Table E.11 Reference directory regarding the relationships between *design decision variables* (Dd) and *performance variables* (Pe) (3/3)

Address		Sources of the itemised knowledge units				
MDdPe		AM	BS8206-1	BS8206-2	U.B.	Others
27	1	-	-	68	-	**BS7[1]**
27	2	-	-	-	**36**	-
27	3	**68, 93**, 94	-	**66, 67, 68, 69, 70**	-	-
27	4	-	-	71	-	-
27	6	-	-	38	-	-
27	7	95	-	**67**	-	-
27	8	-	-	39'	-	-
27	10	**107, 109**	-	**37, 38, 39**, 47, **66**	16, 17	-
27	11	-	-	71	-	-
27	17	-	-	2	-	-
28	5	-	-	-	34	-
28	6	-	-	33', 35'	-	-
28	7	-	-	-	13	-
28	10	-	-	**36**	**29**	-
28	17	-	-	2	-	-
29	1	**29'**	-	**75**	**43**	-
29	5	-	-	50, 51, **54, 55, 56**, 61	-	-
29	6	-	-	**52, 56**	**38, 40**	-
29	7	**58, 87, 121**, 122, 123,124, 125	-	19, 31, 32, 38	39	-
29	8	-	-	-	37	-
29	9	-	-	50, **53**	-	-
29	10	-	-	**37, 38, 52**	16	-
30	1	-	17, **18**	-	47, 48	BS7[1]
30	5	-	-	-	-	CIBSE[4]
30	6	-	-	-	-	CIBSE[4]
30	16	-	14	-	-	-
31	1	-	17, **19**	-	28, 44, **46**	BS7[1]
31	8	-	**10, 11**	57, **63**	**27**, 28	CIBSE[4]
31	10	-	-	-	29	-
31	16	-	**14, 19**	-	-	-
32	1	-	17, **20, 21**	-	46	-
32	10	-	20	**57**	27	-
32	16	-	14	-	-	-
33	1	-	-	-	-	BS7[1]
33	6	-	-	-	**21, 26, 38, 40, 41**	-
33	9	-	-	62	-	-
33	10	-	-	-	29	-
33	16	-	14	-	-	-
34	1	130, 131, 132	**4, 13, 16**, 22, 33', 33"	**75**, 79, **86**	48	BS7[1]
34	6	-	32'	-	-	-
34	16	126, 132	**14**, 32, 34	-	-	-

Table E.12 M_{DdDd}: Matrix representing the relationships between *design decision variables* (Dd) themselves

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		d01	d02	d03	d04	d05	d06	d07	d08	d09	d10	d11	d12	d13	d14	d15	d16	d17	d18	d19	d20	d21	d22	d23	d24	d25	d26	d27	d28	d29	d30	d31	d32	d33	d34
1	Dd_01						1	1	1	1		1			1	1					1			1		1	1	1		1					
2	Dd_02			1			1	1	1	1		1			1				1	1					1		1	1							
3	Dd_03		1					1				1												1		1	1	1							
4	Dd_04								1							1	1	1							1		1								
5	Dd_05	1	1		1							1					1	1							1	1	1								
6	Dd_06																																		
7	Dd_07											1																							
8	Dd_08						1			1	1	1							1		1			1	1	1	1			1					
9	Dd_09								1		1								1									1							
10	Dd_10																		1																
11	Dd_11																						1		1	1		1		1					
12	Dd_12																					1				1	1								
13	Dd_13														1																				
14	Dd_14															1										1									
15	Dd_15														1		1									1	1			1					
16	Dd_16																	1							1		1	1							
17	Dd_17																																		
18	Dd_18																						1					1							
19	Dd_19																				1														
20	Dd_20															1				1			1												
21	Dd_21															1							1					1			1			1	
22	Dd_22															1												1							
23	Dd_23																								1	1	1								
24	Dd_24																									1	1	1							
25	Dd_25															1									1										
26	Dd_26															1												1		1	1	1		1	
27	Dd_27																				1					1									
28	Dd_28															1					1					1				1					
29	Dd_29																														1	1		1	1
30	Dd_30																																		1
31	Dd_31																																1		1
32	Dd_32																															1			
33	Dd_33																																		1
34	Dd_34																																	1	

Table E.13 Reference directory regarding the relationships between *design decision variables* (Dd) themselves (1/3)

Address		Sources of the itemised knowledge units				
MDdDd		AM	BS8206-1	BS8206-2	U.B.	Others
1	6	**9, 11, 35**	-	-	-	-
1	7	**9, 11, 35**	-	-	-	-
1	8	**9, 11, 35**, 50	2	-	**7, 8, 9, 14**	-
1	9	**9**, 11, 50	-	-	9, 11	-
1	11	35	2	-	**7**, 14	-
1	14	**9, 11**, 35	-	-	14	-
1	15	9, 11, **82, 83, 84, 85**	-	-	14	-
1	20	**45**	-	15	-	-
1	23	11	-	**5**	-	-
1	25	45	-	11, **15**	**1**	-
1	26	-	-	-	2	-
1	27	12	-	-	-	-
1	29	10	-	41, 49	-	-
2	3	17	-	-	-	-
2	6	**13, 35**	-	**23**	-	-
2	7	**13**, 17, 35	-	**23**	-	-
2	8	35	-	**23**	-	-
2	9	**45**	-	-	-	Lecture_93
2	11	**15, 17**, 35, 38	-	**23, 24, 65**	-	-
2	14	35, 38	-	**23, 65**	-	-
2	18	**51, 52, 53**, 67	-	-	-	Lecture_93
2	19	54, **71**	-	**21, 68**	-	-
2	24	**94**	-	21, 68	-	-
2	26	15	-	**23, 24, 65**	-	-
2	27	14	-	**21, 65, 66, 67, 68, 69, 69', 70**	-	-
3	2	17	-	-	-	-
3	7	17	-	-	-	-
3	11	17	-	-	-	-
3	23	-	-	5	-	-
3	25	104	-	**14, 15**	-	-
3	26	-	-	**12**	3, 4	-
3	27	-	-	**71**	-	-
4	8	**18**, 29'	-	75	-	-
4	15	18	-	-	-	-
4	16	**18, 18', 28**	-	-	-	-
4	17	**18**, 18', **28**	-	-	-	-
4	24	**18**, 18', 19	-	-	-	-
4	26	-	-	-	5	-
5	1	19	-	-	-	-
5	2	19	-	-	-	-
5	4	19	-	-	-	-
5	11	19	-	-	-	-
5	16	19	-	-	-	-
5	17	19	-	-	-	-
5	24	**18'**, 19, 30, 99	-	-	-	-
5	25	19, 30, **99**	-	-	-	-
5	26	30	-	-	-	-
7	11	**20**, 36, 38	-	-	-	-

Table E.13 Reference directory regarding the relationships between *design decision variables* (Dd) themselves (2/3)

Address		Sources of the itemised knowledge units				
MDdDd		AM	BS8206-1	BS8206-2	U.B.	Others
8	6	35	-	-	-	-
8	9	**50**	-	-	**9**	-
8	10	-	-	-	**9**	-
8	11	**20, 32**	-	-	-	-
8	18	**50, 51**	-	-	-	-
8	20	32	-	-	-	-
8	23	**20, 29'**	-	-	-	-
8	24	**20, 32**	-	-	-	-
8	25	**20, 32**	-	-	**1**	-
8	26	**20, 33**	-	-	-	-
8	29	125	**2**	-	8, **45**	-
9	8	**50**	-	-	**9**	-
9	10	**35**			**7, 11**	
9	18	**51**, 52, 53	-	-	-	-
9	27	45	-	-	-	-
10	18	**51**, 52, 53	-	-	-	-
11	22	-	-	80	-	-
11	24	-	-	**68, 80**	-	-
11	25	-	-	80	-	-
11	27	**96, 97**	-	65, 66	-	CIBSE [1], [2]
11	29	-	2	**19**	-	-
12	21	76	-	-	-	-
12	25	-	-	2	-	-
12	26	-	-	**2**	**6**	-
13	14	-	-	-	-	BS7[3]
14	15	**35, 79**	-	-	-	-
14	25	**88**	-	11	8	-
15	14	-	-	-	8	-
15	16	18	-	-	-	-
15	25	**88**	-	11	8	-
15	26	**82, 83, 84, 85**	-	11	-	-
15	29	**125**	-	**34**	-	-
16	17	**18, 28**	-	-	-	-
16	24	18	-	-	-	-
16	26	**103**	-	-	**5**	-
16	27	-	-	71	-	-
18	22	37, 52, **78**	-	-	-	-
18	27	-	-	66	-	CIBSE[2]
19	20	**55, 56**	-	68	-	-
20	15	36	-	-	-	-
20	19	**55, 56**	-	68	-	-
20	22	78	-	-	-	-
21	15	36	-	-	-	-
21	22	37, **78**	-	-	-	-
21	27	-	-	66	-	-
21	30	-	-	-	-	CIBSE[6]
21	33	125	-	-	-	CIBSE[7]
22	15	36	-	-	-	-
22	27	-	-	66	-	CIBSE[2]

Table E.13 Reference directory regarding the relationships between *design decision variables* (Dd) themselves (3/3)

Address		Sources of the itemised knowledge units				
MDdDd		AM	BS8206-1	BS8206-2	U.B.	Others
23	24	**81, 86**	-	-	5, **6**	-
23	25	-	-	**14, 15**	-	-
23	26	-	-	-	2	-
24	25	**86, 88**	-	**80**	-	-
24	26	18'	-	-	-	-
24	27	**18'**, 68	-	-	-	-
25	15	36	-	-	-	-
25	24	86, 88	-	**68**, 80	-	-
26	15	36, **82, 83, 84, 85**	-	-	-	-
26	27	96, 97	-	**66, 67, 68, 69, 70**	-	CIBSE[1]
26	29	125	-	**34**	45	-
26	30	-	-	-	-	CIBSE[6]
26	31	-	-	-	37	-
26	33	125	-	-	-	CIBSE[7]
27	20	-	-	67	-	-
27	25	-	-	67	-	-
28	15	84	-	-	-	-
28	20	61	-	-	**1**	-
28	25	61, **88**	-	-	1	-
28	29	-	-	54	-	-
29	30	**124**	-	-	32	-
29	31	**125**	**3**	-	37	-
29	33	**125**	**3**	-	-	-
29	34	58, 87, 122, 123, **124**	28, 32, 33'	64	-	-
30	34	125	28, 29, **32'**	64	32	-
31	32	-	-	-	-	CIBSE[3][4][5]
31	34	**130, 131**	**33'**	-	-	CIBSE[4]
32	31	-	-	-	-	CIBSE[3][4][5]
33	34	125, 127	**32'**	64	-	-
34	33	**125, 127**	29	-	-	-

E.3 Lists of the Associated *Design Variables*

Having represented in a matrix form, the lists of associated *design variables* were developed with regard to each of the individual desgin variables. Within these list, the names of the associated *design variables* are shown, together with the addresses of the relationships, under the particular *design variable* to consider, which is presented in bold.

(1) The design variables associated with *Information variables*

The conditions represented by the *information variables* (In) may need to be considered, when design targets (performance criteria) are established, and/or when the design decisions are made and evaluated. The lists of the design variables associated with an *information variable* may, therefore, involve *performance criteria* (Pc) as well as *performance variables* (Pe) and *design decision variables* (Dd).

In_01	**Aim of the project**	
Pc_01	Energy targets	$M_{InPc}(1, 1)$
Dd_01	Daylight priorities	$M_{InDd}(1, 1)$
Dd_03	View priorities	$M_{InDd}(1, 3)$
Dd_04	Ventilation priorities	$M_{InDd}(1, 4)$

(No *performance variable* for evaluation (Pe) was associated with this *information variable.*)

In_02	**Budget**	
Pc_01	Energy targets	$M_{InPc}(2, 1)$
Pc_16	Cost range criteria (construction)	$M_{InPc}(2, 9)$

(No *performance variable* for evaluation (Pe) or *design decision variable* (Dd) was associated with this *information variable.*)

In_03 **Time table**

(No design variable was found to be associated with this *information variable.*)

In_04	**Use of the building**	
Pe_01	Energy consumption	$M_{InPe}(4, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(4, 2)$
Dd_12	Construction type	$M_{InDd}(4, 12)$

(No *performance criterion* (Pc) was associated with this *information variable.*)

In_05	**Accommodation**	
Pc_07	Target ADF	$M_{InPc}(5, 6)$
Pe_07	Average daylight factor (ADF)	$M_{InPe}(5, 7)$
Dd_13	Functional connections of internal spaces	$M_{InDd}(5, 13)$
Dd_14	Accommodation plan	$M_{InDd}(5, 14)$

In_06	**Activities carried out**	
Pc_05	Illuminance level required	$M_{InPc}(6, 4)$
Pc_06	Uniformity required	$M_{InPc}(6, 5)$
Pc_08	Colour properties required	$M_{InPc}(6, 7)$
Pc_13	Noise insulation level required	$M_{InPc}(6, 8)$
Pe_01	Energy consumption	$M_{InPe}(6, 1)$
Pe_10	Glare and specular reflection	$M_{InPe}(6, 10)$
Dd_01	Daylight priorities	$M_{InDd}(6, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(6, 2)$
Dd_03	View priorities	$M_{InDd}(6, 3)$
Dd_05	Noise insulation priorities	$M_{InDd}(6, 5)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(6, 11)$
Dd_13	Functional connections	$M_{InDd}(6, 13)$
Dd_18	Rooflight profiles	$M_{InDd}(6, 18)$
Dd_22	Area and dimension of individual rooflight	$M_{InDd}(6, 22)$
Dd_25	Glazed area for side windows	$M_{InDd}(6, 25)$
Dd_26	Window shapes and positions	$M_{InDd}(6, 26)$
Dd_30	Lighting system	$M_{InDd}(6, 30)$
Dd_31	Lamp types	$M_{InDd}(6, 31)$
Dd_32	Lighting luminaires	$M_{InDd}(6, 32)$

In_07	**Visual tasks**	
Pc_05	Illuminance level required	$M_{InPc}(7, 4)$
Pc_06	Uniformity required	$M_{InPc}(7, 5)$
Pc_08	Colour properties required	$M_{InPc}(7, 7)$
Dd_01	Daylight priorities	$M_{InDd}(7, 1)$
Dd_20	Glazed area for rooflights	$M_{InDd}(7, 20)$
Dd_25	Glazed area for side windows	$M_{InDd}(7, 25)$
Dd_30	Lighting system	$M_{InDd}(7, 30)$
Dd_31	Lamp types	$M_{InDd}(7, 31)$

(No *performance variable* for evaluation (Pe) was associated with this *information variable.*)

In_08	**Occupation patterns**	
Pc_07	Target ADF	$M_{InPc}(8, 6)$
Pe_01	Energy consumption	$M_{InPe}(8, 1)$
Dd_01	Daylight priorities	$M_{InDd}(8, 1)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(8, 11)$
Dd_12	Construction type	$M_{InDd}(8, 12)$
Dd_22	Area and dimension of individual rooflight	$M_{InDd}(8, 22)$
Dd_26	Window shapes and positions	$M_{InDd}(8, 26)$

Dd_34	Lighting control system	$M_{InDd}(8, 34)$
In_09	**Boundaries**	
Pe_12	Privacy	$M_{InPe}(9, 12)$
Pe_15	Overshadowing	$M_{InPe}(9, 15)$
Dd_01	Daylight priorities	$M_{InDd}(9, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(9, 2)$
Dd_06	Position of the building on the site	$M_{InDd}(9, 6)$
Dd_07	Orientation of the building	$M_{InDd}(9, 7)$
Dd_08	Form of the building	$M_{InDd}(9, 8)$
Dd_23	Primary function of side windows	$M_{InDd}(9, 23)$
Dd_25	Glazed area for side windows	$M_{InDd}(9, 25)$
Dd_26	Window shapes and positions	$M_{InDd}(9, 26)$

(No *performance criterion* (Pc) was associated with this *information variable.*)

In_10	**Daylight availability**	
Pc_07	Target ADF	$M_{InPc}(10, 6)$
Pe_02	Heat loss	$M_{InPe}(10, 2)$
Pe_03	Solar gain	$M_{InPe}(10, 3)$
Pe_07	Average daylight factor (ADF)	$M_{InPe}(10, 7)$
Pe_15	Overshadowing	$M_{InPe}(10, 15)$
Dd_01	Daylight priorities	$M_{InDd}(10, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(10, 2)$
Dd_06	Position of the building on the site	$M_{InDd}(10, 6)$
Dd_07	Orientation of the building	$M_{InDd}(10, 7)$
Dd_08	Form of the building	$M_{InDd}(10, 8)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(10, 11)$
Dd_15	Room depth	$M_{InDd}(10, 15)$
Dd_20	Glazed area for rooflights	$M_{InDd}(10, 20)$
Dd_21	Number and position of rooflights	$M_{InDd}(10, 21)$
Dd_22	Area and dimension of individual rooflight	$M_{InDd}(10, 22)$
Dd_23	Primary function of side windows	$M_{InDd}(10, 23)$
Dd_25	Glazed area for side windows	$M_{InDd}(10, 25)$
Dd_26	Window shapes and positions	$M_{InDd}(10, 26)$
Dd_29	Function of artificial lighting	$M_{InDd}(10, 29)$
In_11	**Sunlight duration**	
Pe_02	Heat loss	$M_{InPc}(11, 2)$
Pe_03	Solar gain	$M_{InPe}(11, 3)$
Dd_02	Sunshine priorities	$M_{InDd}(11, 2)$
Dd_27	Shading devices	$M_{InDd}(11, 27)$

(No *performance criterion* (Pc) was associated with this *information variable.*)

In_12	**View**	
Pe_11	View	$M_{InPe}(12, 11)$
Dd_03	View priorities	$M_{InDd}(12, 3)$
Dd_25	Glazed area for side windows	$M_{InDd}(12, 25)$

Dd_26	Window shapes and positions	$M_{InDd}(12, 26)$

(No *performance criterion* (Pc) was associated with this *information variable.*)

In_13	**Noise sources**	
Pe_13	Noise level within the building	$M_{InPe}(13, 13)$
Dd_01	Daylight priorities	$M_{InDd}(13, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(13, 2)$
Dd_04	Ventilation priorities	$M_{InDd}(13, 4)$
Dd_05	Noise insulation priorities	$M_{InDd}(13, 5)$
Dd_06	Position of the building on the site	$M_{InDd}(13, 6)$
Dd_07	Orientation of the building	$M_{InDd}(13, 7)$
Dd_08	Form of the building	$M_{InDd}(13, 8)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(13, 11)$
Dd_16	Use of natural ventilation	$M_{InDd}(13, 16)$
Dd_17	Need for mechanical ventilation or air-conditioning	$M_{InDd}(13, 17)$
Dd_18	Rooflight profiles	$M_{InDd}(13, 18)$
Dd_24	Glazing material for side windows	$M_{InDd}(13, 24)$
Dd_25	Glazed area for side windows	$M_{InDd}(13, 25)$
Dd_26	Window shapes and positions	$M_{InDd}(13, 26)$

(No *performance variable* for performance criterion (Pc) was associated with this *information variable.*)

In_14	**Physical pollution**	
Dd_01	Daylight priorities	$M_{InDd}(14, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(14, 2)$
Dd_03	View priorities	$M_{InDd}(14, 3)$
Dd_04	Ventilation priorities	$M_{InDd}(14, 4)$
Dd_06	Position of the building on the site	$M_{InDd}(14, 6)$
Dd_07	Orientation of the building	$M_{InDd}(14, 7)$
Dd_08	Form of the building	$M_{InDd}(14, 8)$
Dd_09	Use of rooflights	$M_{InDd}(14, 9)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(14, 11)$
Dd_16	Use of natural ventilation	$M_{InDd}(14, 16)$
Dd_17	Need for mechanical ventilation or air-conditioning	$M_{InDd}(14, 17)$
Dd_18	Rooflight profiles	$M_{InDd}(14, 18)$
Dd_20	Glazed area for rooflights	$M_{InDd}(14, 20)$
Dd_24	Glazing material for side windows	$M_{InDd}(14, 24)$
Dd_25	Glazed area for side windows	$M_{InDd}(14, 25)$
Dd_26	Window shapes and positions	$M_{InDd}(14, 26)$

(No *performance criterion* (Pc) or *performance variable* for performance criterion (Pe) was associated with this *information variable.*)

In_15	**Ambient climate**	
Pe_01	Energy consumption	$M_{InPe}(15, 1)$
Pe_02	Heat loss	$M_{InPe}(15, 2)$
Dd_01	Daylight priorities	$M_{InDd}(15, 1)$
Dd_02	Sunshine priorities	$M_{InDd}(15, 2)$

Dd_04	Ventilation priorities	$M_{InDd}(15, 4)$
Dd_06	Position of the building on the site	$M_{InDd}(15, 6)$
Dd_07	Orientation of the building	$M_{InDd}(15, 7)$
Dd_08	Form of the building	$M_{InDd}(15, 8)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(15, 11)$
Dd_16	Use of natural ventilation	$M_{InDd}(15, 16)$
Dd_18	Rooflight profiles	$M_{InDd}(15, 18)$
Dd_20	Glazed area for rooflights	$M_{InDd}(15, 20)$
Dd_24	Glazing material for side windows	$M_{InDd}(15, 24)$
Dd_25	Glazed area for side windows	$M_{InDd}(15, 25)$
Dd_31	Lamp types	$M_{InDd}(15, 31)$

(No *performance criterion* (Pc) was associated with this *information variable.*)

In_16	**Local authorities and statutory regulations**	
Dd_06	Position of the building on the site	$M_{InDd}(16, 6)$
Dd_07	Orientation of the building	$M_{InDd}(16, 7)$
Dd_08	Form of the building	$M_{InDd}(16, 8)$
Dd_11	Glazing orientation and related glazing area	$M_{InDd}(16, 11)$
Dd_20	Glazed area for rooflights	$M_{InDd}(16, 20)$
Dd_25	Glazed area for side windows	$M_{InDd}(16, 25)$

(No *performance criterion* (Pc) or *performance variable* for performance criterion (Pe) was associated with this *information variable.*)

(2) The design variables associated with *Performance criteria*

During the briefing stage, *performance criteria* (Pc) are established in relation to some of the *performance variables* (Pe). The conditions represented by the *information variables* (In) may need to be taken into account when these *performance criteria* are established. The lists of the design variables associated with the *performance criteria* may, therefore, involve *information variables* (In) associated with a particular *performance criterion*.

Pc_01	**Energy targets**	
Pe_01	Energy consumption	
In_01	Aim of the project	$M_{InPc}(1, 1)$
In_02	Budget	$M_{InPc}(2, 1)$

Pc_03	**Thermal comfort level**	
Pe_03	Solar gain	
In_06	Activities carried out	$M_{InPc}(6, 2)$

Pc_04	**Air qualities required**	
Pe_04	Ventilation performance	
In_06	Activities carried out	$M_{InPc}(6, 3)$
Pc_05	**Illuminance level required**	
Pe_05	Illuminance level on a working plane	
In_06	Activities carried out	$M_{InPc}(6, 4)$
In_07	Visual tasks	$M_{InPc}(7, 4)$
Pc_06	**Uniformity required**	
Pe_06	Uniformity of illuminance level	
In_06	Activities carried out	$M_{InPc}(6, 5)$
In_07	Visual tasks	$M_{InPc}(7, 5)$
Pc_07	**Target average daylight factor**	
Pe_07	Average daylight factor (ADF)	
In_05	Accommodation	$M_{InPc}(5, 6)$
In_08	Occupation patterns	$M_{InPc}(8, 6)$
In_10	Daylight availability	$M_{InPc}(10, 6)$
Pc_08	**Colour properties required**	
Pe_08	Colour properties	
In_06	Activities carried out	$M_{InPc}(6, 7)$
In_07	Visual tasks	$M_{InPc}(7, 7)$
Pc_13	**Noise insulation level required**	
Pe_13	Noise level within the building	
In_06	Activities carried out	$M_{InPc}(6, 8)$
Pc_16	**Cost range criteria (construction)**	
Pe_16	Cost	
In_02	Budget	$M_{InPc}(2, 9)$

(3) The design variables associated with *design decision variables*

It was considered that the design decisions were made in terms of the *design decision variables* (Dd) when a design solution is being developed. During the development of design solutions, some design decisions may require the conditions (i.e. the requirements and constraints) represented by the *information variables* (In) to be considered. Making a design decision may also require the consideration of the preceding design decisions since they may restrict that particular design decision. The lists of design variables associated with the *design decision variables* (Dd) may, therefore, involve the *information variables* (In). It was considered, meanwhile, that the design decisions were evaluated in terms of the performance characteristics represented by *performance variables* for evaluation (Pe), and then these charactersistcs were referred back to the original design decisions. Therefore, the lists associated with each of the *design decision variables* also include the *performance variables* (Pe) representing the performance characteristics which have to be considered in relation to that particular design decision.

Dd_01	**Daylight priorities**	
In_01	Aim of the project	$M_{InDd}(1, 1)$
In_06	Activities carried out	$M_{InDd}(6, 1)$
In_07	Visual tasks	$M_{InDd}(7, 1)$
In_08	Occupation patterns	$M_{InDd}(8, 1)$
In_09	Boundaries	$M_{InDd}(9, 1)$
In_10	Daylight availability	$M_{InDd}(10, 1)$
In_13	Noise sources	$M_{InDd}(13, 1)$
In_14	Physical pollution	$M_{InDd}(14, 1)$
In_15	Ambient climate	$M_{InDd}(15, 1)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 1)$
Pe_01	Energy consumption	$M_{DdPe}(1, 1)$
Pe_02	Heat loss	$M_{DdPe}(1, 2)$
Pe_03	Solar gain	$M_{DdPe}(1, 3)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(1, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(1, 7)$
Pe_08	Colour properties	$M_{DdPe}(1, 8)$
Pe_09	Appearance / modelling	$M_{DdPe}(1, 9)$
Pe_10	Glare and specular reflection	$M_{DdPe}(1, 10)$
Pe_11	View	$M_{DdPe}(1, 11)$

Dd_02 Sunshine priorities

In_04	Use of the building	$M_{InDd}(4, 2)$
In_06	Activities carried out	$M_{InDd}(6, 2)$
In_09	Boundaries	$M_{InDd}(9, 2)$
In_10	Daylight availability	$M_{InDd}(10, 2)$
In_11	Sunlight duration	$M_{InDd}(11, 2)$
In_13	Noise sources	$M_{InDd}(13, 2)$
In_14	Physical pollution	$M_{InDd}(14, 2)$
In_15	Ambient climate	$M_{InDd}(15, 2)$
Dd_03	View priorities	$M_{DdDd}(3, 2)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 2)$
Pe_01	Energy consumption	$M_{DdPe}(2, 1)$
Pe_03	Solar gain	$M_{DdPe}(2, 3)$
Pe_10	Glare and specular reflection	$M_{DdPe}(2, 10)$

Dd_03 View priorities

In_01	Aim of the project	$M_{InDd}(1, 3)$
In_06	Activities carried out	$M_{InDd}(6, 3)$
In_12	View	$M_{InDd}(12, 3)$
In_14	Physical pollution	$M_{InDd}(14, 3)$
Dd_02	Sunshine priorities	$M_{DdDd}(3, 2)$
Pe_11	View	$M_{DdPe}(3, 11)$
Pe_12	Privacy	$M_{DdPe}(3, 12)$

Dd_04 Ventilation priorities

In_01	Aim of the project	$M_{InDd}(1, 4)$
In_13	Noise sources	$M_{InDd}(13, 4)$
In_14	Physical pollution	$M_{InDd}(14, 4)$
In_15	Ambient climate	$M_{InDd}(15, 4)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 4)$

(No *performance variable for evaluation* (Pe) was associated with this *design decision variable.*)

Dd_05 Noise insulation priorities

In_06	Activities carried out	$M_{InDd}(6, 5)$
In_13	Noise sources	$M_{InDd}(13, 5)$

(No *performance variable for evaluation* (Pe) or *design decision variable* was associated with this *design decision variable.*)

Dd_06 Position of the building on the site

In_09	Boundaries	$M_{InDd}((9, 6)$
In_10	Daylight availability	$M_{InDd}(10, 6)$
In_13	Noise sources	$M_{InDd}(13, 6)$
In_14	Physical pollution	$M_{InDd}(14, 6)$
In_15	Ambient climate	$M_{InDd}(15, 6)$
In_16	Local authorities and statutory regulations	$M_{InDd}(16, 6)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 6)$

Dd_02	Sunshine priorities	$M_{DdDd}(2, 6)$
Dd_08	Form of the building	$M_{DdDd}(8, 6)$
Pe_03	Solar gain	$M_{DdPe}(6, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(6, 7)$
Pe_11	View	$M_{DdPe}(6, 11)$
Pe_12	Privacy	$M_{DdPe}(6, 12)$
Pe_15	Overshadowing	$M_{DdPe}(6, 15)$

Dd_07	**Orientation of the building**	
In_09	Boundaries	$M_{InDd}(9, 7)$
In_10	Daylight availability	$M_{InDd}(10, 7)$
In_13	Noise sources	$M_{InDd}(13, 7)$
In_14	Physical pollution	$M_{InDd}(14, 7)$
In_15	Ambient climate	$M_{InDd}(15, 7)$
In_16	Local authorities and statutory regulations	$M_{InDd}(16, 7)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 7)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 7)$
Dd_03	View priorities	$M_{DdDd}(3, 7)$
Pe_03	Solar gain	$M_{DdPe}(7, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(7, 7)$
Pe_11	View	$M_{DdPe}(7, 11)$
Pe_12	Privacy	$M_{DdPe}(7, 12)$
Pe_15	Overshadowing	$M_{DdPe}(7, 15)$

Dd_08	**Form of the building**	
In_09	Boundaries	$M_{InDd}(9, 8)$
In_10	Daylight availability	$M_{InDd}(10, 8)$
In_13	Noise sources	$M_{InDd}(13, 8)$
In_14	Physical pollution	$M_{InDd}(14, 8)$
In_15	Ambient climate	$M_{InDd}(15, 8)$
In_16	Local authorities and statutory regulations	$M_{InDd}(16, 8)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 8)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 8)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 8)$
Dd_09	Use of rooflights	$M_{DdDd}(9, 8)$
Pe_01	Energy consumption	$M_{DdPe}(8, 1)$
Pe_02	Heat loss	$M_{DdPe}(8, 2)$
Pe_03	Solar gain	$M_{DdPe}(8, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(8, 7)$
Pe_12	Privacy	$M_{DdPe}(8, 12)$
Pe_15	Overshadowing	$M_{DdPe}(8, 15)$
Pe_16	Cost	$M_{DdPe}(8, 16)$
Pe_17	Aesthetics	$M_{DdPe}(8, 17)$

Dd_09	**Use of rooflights**	
In_14	Physical pollution	$M_{InDd}(14, 9)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 9)$

Dd_02	Sunshine priorities	$M_{\mathrm{DdDd}}(2, 9)$
Dd_08	Form of the building	$M_{\mathrm{DdDd}}(8, 9)$
Pe_02	Heat loss	$M_{\mathrm{DdPe}}(9, 2)$
Pe_03	Solar gain	$M_{\mathrm{DdPe}}(9, 3)$
Pe_06	Uniformity of illuminance level	$M_{\mathrm{DdPe}}(9, 6)$
Pe_09	Appearance / modelling	$M_{\mathrm{DdPe}}(9, 9)$

Dd_10 Roof shape

Dd_08	Form of the building	$M_{\mathrm{DdDd}}(8, 10)$
Dd_09	Use of rooflights	$M_{\mathrm{DdDd}}(9, 10)$
Pe_03	Solar gain	$M_{\mathrm{DdPe}}(10, 3)$

(No *information variable* was associated with this *design decision variable.*)

Dd_11 Glazing orientation and related glazing area

In_06	Activities carried out	$M_{\mathrm{InDd}}(6, 11)$
In_08	Occupation patterns	$M_{\mathrm{InDd}}(8, 11)$
In_10	Daylight availability	$M_{\mathrm{InDd}}(10, 11)$
In_13	Noise sources	$M_{\mathrm{InDd}}(13, 11)$
In_14	Physical pollution	$M_{\mathrm{InDd}}(14, 11)$
In_15	Ambient climate	$M_{\mathrm{InDd}}(15, 11)$
In_16	Local authorities and statutory regulations	$M_{\mathrm{InDd}}(16, 11)$
Dd_01	Daylight priorities	$M_{\mathrm{DdDd}}(1, 11)$
Dd_02	Sunshine priorities	$M_{\mathrm{DdDd}}(2, 11)$
Dd_03	View priorities	$M_{\mathrm{DdDd}}(3, 11)$
Dd_05	Noise insulation priorities	$M_{\mathrm{DdDd}}(5, 11)$
Dd_07	Orientation of the building	$M_{\mathrm{DdDd}}(7, 11)$
Dd_08	Form of the building	$M_{\mathrm{DdDd}}(8, 11)$
Pe_01	Energy consumption	$M_{\mathrm{DdPe}}(11, 1)$
Pe_02	Heat loss	$M_{\mathrm{DdPe}}(11, 2)$
Pe_03	Solar gain	$M_{\mathrm{DdPe}}(11, 3)$
Pe_07	Average daylight factor (ADF)	$M_{\mathrm{DdPe}}(11, 7)$
Pe_10	Glare and specular reflection	$M_{\mathrm{DdPe}}(11, 10)$
Pe_12	Privacy	$M_{\mathrm{DdPe}}(11, 12)$

Dd_12 Construction type

In_04	Use of the building	$M_{\mathrm{InDd}}(4, 12)$
In_08	Occupation patterns	$M_{\mathrm{InDd}}(8, 12)$
Pe_01	Energy consumption	$M_{\mathrm{DdPe}}(12, 1)$
Pe_02	Heat loss	$M_{\mathrm{DdPe}}(12, 2)$

(No *design decision variable* was associated with this *design decision variable.*)

Dd_13 Functional connections of internal spaces

In_05	Accommodation	$M_{\mathrm{InDd}}(5, 13)$
In_06	Activities carried out	$M_{\mathrm{InDd}}(6, 13)$
Pe_05	Illuminance level on a working plane	$M_{\mathrm{DdPe}}(13, 5)$

(No *design decision variable* or *design decision variable* was associated with this *design decision variables.*)

Dd_14	**Accommodation plan**	
In_05	Accommodation	$M_{InDd}(5, 14)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 14)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 14)$
Dd_13	Functional connections	$M_{DdDd}(13, 14)$
Dd_15	Room depth	$M_{DdDd}(15, 14)$
Pe_03	Solar gain	$M_{DdPe}(14, 3)$
Pe_05	Illuminance level on a working plane	$M_{DdPe}(14, 5)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(14, 7)$
Pe_08	Colour properties	$M_{DdPe}(14, 8)$
Pe_09	Appearance / modelling	$M_{DdPe}(14, 9)$

Dd_15	**Room depth**	
In_10	Daylight availability	$M_{InDd}(10,15)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 15)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 15)$
Dd_14	Accommodation plan	$M_{DdDd}(14, 25)$
Dd_20	Glazed area for rooflights	$M_{DdDd}(20, 15)$
Dd_21	Number and position of rooflights	$M_{DdDd}(21, 15)$
Dd_22	Area and dimension of individual rooflight	$M_{DdDd}(22, 15)$
Dd_25	Glazed area for side windows	$M_{DdDd}(25, 15)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 15)$
Dd_28	Reflectance of the interior	$M_{DdDd}(28, 15)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(15, 7)$
Pe_11	View	$M_{DdPe}(15, 11)$

Dd_16	**Use of natural ventilation**	
In_13	Noise sources	$M_{InDd}(13, 16)$
In_14	Physical pollution	$M_{InDd}(14, 16)$
In_15	Ambient climate	$M_{InDd}(15, 16)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 16)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 16)$
Dd_15	Room depth	$M_{DdDd}(15, 16)$
Pe_01	Energy consumption	$M_{DdPe}(16, 1)$
Pe_02	Heat loss	$M_{DdPe}(16, 2)$

Dd_17	**Need for mechanical ventilation or air-conditioning**	
In_13	Noise sources	$M_{InDd}(13, 17)$
In_14	Physical pollution	$M_{InDd}(14, 17)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 17)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 17)$
Dd_16	Use of natural ventilation	$M_{DdDd}(16, 17)$
Pe_01	Energy consumption	$M_{DdPe}(17, 1)$
Pe_02	Heat loss	$M_{DdPe}(17, 2)$

Dd_18	**Rooflight profile**	
In_06	Activities carried out	$M_{InDd}(6, 18)$
In_13	Noise sources	$M_{InDd}(13, 18)$
In_14	Physical pollution	$M_{InDd}(14, 18)$
In_15	Ambient climate	$M_{InDd}(15, 18)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 18)$
Dd_08	Form of the building	$M_{DdDd}(8, 18)$
Dd_09	Use of rooflight	$M_{DdDd}(9, 18)$
Dd_10	Roof shape	$M_{DdDd}(10,18)$
Pe_02	Heat loss	$M_{DdPe}(18, 2)$
Pe_03	Solar gain	$M_{DdPe}(18, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(18, 7)$
Pe_09	Appearance / modelling	$M_{DdPe}(18, 9)$

Dd_19	**Glazing materials for rooflight**	
Dd_02	Sunshine priorities	$M_{DdDd}(2, 19)$
Dd_20	Glazed area for rooflights	$M_{DdDd}(20, 19)$
Pe_02	Heat loss	$M_{DdPe}(19, 2)$
Pe_03	Solar gain	$M_{DdPe}(19, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(19, 7)$
Pe_08	Colour properties	$M_{DdPe}(19, 8)$
Pe_10	Glare and specular reflection	$M_{DdPe}(19, 10)$

(No *information variable* was associated with this *design decision variable.*)

Dd_20	**Glazed area for rooflights**	
In_07	Visual tasks	$M_{InDd}(7, 20)$
In_10	Daylight availability	$M_{InDd}(10, 20)$
In_14	Physical pollution	$M_{InDd}(14, 20)$
In_15	Ambient climate	$M_{InDd}(15, 20)$
In_16	Local authorities and statutory regulations	$M_{InDd}(16, 20)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 20)$
Dd_08	Form of the building	$M_{DdDd}(8, 20)$
Dd_19	Glazing materials for rooflights	$M_{DdDd}(19, 20)$
Dd_27	Shading devices	$M_{DdDd}(27, 20)$
Dd_28	Reflectance of the interior	$M_{DdDd}(28, 20)$
Pe_01	Energy consumption	$M_{DdPe}(20, 1)$
Pe_02	Heat loss	$M_{DdPe}(20, 2)$
Pe_03	Solar gain	$M_{DdPe}(20, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(20, 7)$

Dd_21	**Number and position of rooflights**	
In_10	Daylight availability	$M_{InDd}(10, 21)$
Dd_12	Construction type	$M_{DdDd}(12, 21)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(21, 6)$
Pe_10	Glare and specular reflection	$M_{DdPe}(21, 10)$
Pe_14	Structure	$M_{DdPe}(21, 14)$

Dd_22	**Area and dimension of individual rooflights**	
In_06	Activities carried out	$M_{InDd}(6, 22)$
In_08	Occupation patterns	$M_{InDd}(8, 22)$
In_10	Daylight availability	$M_{InDd}(10, 22)$
Dd_11	Glazing orientation and related glazing area	$M_{DdDd}(11, 22)$
Dd_18	Rooflight profiles	$M_{DdDd}(18, 22)$
Dd_20	Glazed area for rooflights	$M_{DdDd}(20, 22)$
Dd_21	Number and position of rooflights	$M_{DdDd}(21, 22)$
Pe_02	Heat loss	$M_{DdPe}(22, 2)$
Pe_03	Solar gain	$M_{DdPe}(22, 3)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(22, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(22, 7)$
Pe_10	Glare and specular reflection	$M_{DdPe}(22, 10)$

Dd_23	**Primary function of side windows**	
In_09	Boundaries	$M_{InDd}(9, 23)$
In_10	Daylight availability	$M_{InDd}(10, 23)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 23)$
Dd_03	View priorities	$M_{DdDd}(3, 23)$
Dd_08	Form of the building	$M_{DdDd}(8, 23)$
Pe_09	Appearance / modelling	$M_{DdPe}(23, 9)$
Pe_17	Aesthetics	$M_{DdPe}(23, 17)$

Dd_24	**Glazing materials for side windows**	
In_13	Noise sources	$M_{InDd}(13, 24)$
In_14	Physical pollution	$M_{InDd}(14, 24)$
In_15	Ambient climate	$M_{InDd}(15, 24)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 24)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 24)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 24)$
Dd_08	Form of the building	$M_{DdDd}(8, 24)$
Dd_11	Glazing orientation and related glazing area	$M_{DdDd}(11, 24)$
Dd_16	Use of natural ventilation	$M_{DdDd}(16, 24)$
Dd_23	Primary function of side windows	$M_{DdDd}(23, 24)$
Dd_25	Glazed area for side windows	$M_{DdDd}(25, 24)$
Pe_02	Heat loss	$M_{DdPe}(24, 2)$
Pe_03	Solar gain	$M_{DdPe}(24, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(24, 7)$
Pe_08	Colour properties	$M_{DdPe}(24, 8)$
Pe_10	Glare and specular reflection	$M_{DdPe}(24, 10)$
Pe_13	Noise level within the building	$M_{DdPe}(24, 13)$
Pe_17	Aesthetics	$M_{DdPe}(24, 17)$

Dd_25	**Glazed area for side windows**	
In_06	Activities carried out	$M_{InDd}(6, 25)$
In_07	Visual tasks	$M_{InDd}(7, 25)$
In_09	Boundaries	$M_{InDd}(9, 25)$

In_10	Daylight availability	$M_{InDd}(10, 25)$
In_12	View	$M_{InDd}(12, 25)$
In_13	Noise sources	$M_{InDd}(13, 25)$
In_14	Physical pollution	$M_{InDd}(14, 25)$
In_15	Ambient climate	$M_{InDd}(15, 25)$
In_16	Local authorities and statutory regulations	$M_{InDd}(16, 25)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 25)$
Dd_03	View priorities	$M_{DdDd}(3, 25)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 25)$
Dd_08	Form of the building	$M_{DdDd}(8, 25)$
Dd_11	Glazing orientation and related glazing area	$M_{DdDd}(11, 25)$
Dd_12	Construction type	$M_{DdDd}(12, 25)$
Dd_14	Accommodation plan	$M_{DdDd}(14, 25)$
Dd_15	Room depth	$M_{DdDd}(15, 25)$
Dd_23	Primary function of side windows	$M_{DdDd}(23, 25)$
Dd_24	Glazing material for side windows	$M_{DdDd}(24, 25)$
Dd_27	Shading devices	$M_{DdDd}(27, 25)$
Dd_28	Reflectance of the interior	$M_{DdDd}(28, 25)$
Pe_01	Energy consumption	$M_{DdPe}(25, 1)$
Pe_02	Heat loss	$M_{DdPe}(25, 2)$
Pe_03	Solar gain	$M_{DdPe}(25, 3)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(25, 7)$
Pe_11	View	$M_{DdPe}(25, 11)$
Pe_13	Noise level within the building	$M_{DdPe}(25, 13)$
Pe_17	Aesthetics	$M_{DdPe}(25, 17)$
Dd_26	**Window shapes and positions**	
In_06	Activities carried out	$M_{InDd}(6, 26)$
In_08	Occupation patterns	$M_{InDd}(8, 26)$
In_09	Boundaries	$M_{InDd}(9, 26)$
In_10	Daylight availability	$M_{InDd}(10, 26)$
In_12	View	$M_{InDd}(12, 26)$
In_13	Noise sources	$M_{InDd}(13, 26)$
In_14	Physical pollution	$M_{InDd}(14, 26)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 27)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 26)$
Dd_03	View priorities	$M_{DdDd}(3, 26)$
Dd_04	Ventilation priorities	$M_{DdDd}(4, 26)$
Dd_05	Noise insulation priorities	$M_{DdDd}(5, 26)$
Dd_08	Form of the building	$M_{DdDd}(8, 26)$
Dd_12	Construction type	$M_{DdDd}(12, 26)$
Dd_15	Room depth	$M_{DdDd}(15, 26)$
Dd_16	Use of natural ventilation	$M_{DdDd}(16, 26)$
Dd_23	Primary function of side windows	$M_{DdDd}(23, 26)$
Dd_24	Glazing material for side windows	$M_{DdDd}(24, 26)$
Pe_02	Heat loss	$M_{DdPe}(26, 2)$
Pe_03	Solar gain	$M_{DdPe}(26, 3)$

Pe_04	Ventilation performance (air change)	$M_{DdPe}(26, 4)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(26, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(26, 7)$
Pe_09	Appearance / modelling	$M_{DdPe}(26, 9)$
Pe_10	Glare and specular reflection	$M_{DdPe}(26, 10)$
Pe_11	View	$M_{DdPe}(26, 11)$
Pe_12	Privacy	$M_{DdPe}(26, 12)$
Pe_14	Structure	$M_{DdPe}(26, 14)$
Pe_17	Aesthetics	$M_{DdPe}(26, 17)$

Dd_27	**Shading devices**	
In_11	Sunlight duration	$M_{InDd}(11, 27)$
Dd_01	Daylight priorities	$M_{DdDd}(1, 27)$
Dd_02	Sunshine priorities	$M_{DdDd}(2, 27)$
Dd_03	View priorities	$M_{DdDd}(3, 27)$
Dd_09	Use of rooflights	$M_{DdDd}(9, 27)$
Dd_11	Glazing orientation and related glazing area	$M_{DdDd}(11,27)$
Dd_16	Use of natural ventilation	$M_{DdDd}(16, 27)$
Dd_18	Rooflight profiles	$M_{DdDd}(18, 27)$
Dd_21	Number and position of rooflights	$M_{DdDd}(21, 27)$
Dd_22	Area and dimension of individual rooflight	$M_{DdDd}(22, 27)$
Dd_24	Glazing material for side windows	$M_{DdDd}(24, 27)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 27)$
Pe_01	Energy consumption	$M_{DdPe}(27, 1)$
Pe_02	Heat loss	$M_{DdPe}(27, 2)$
Pe_03	Solar gain	$M_{DdPe}(27, 3)$
Pe_04	Ventilation performance (air change)	$M_{DdPe}(27, 4)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(27, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(27, 7)$
Pe_08	Colour properties	$M_{DdPe}(27, 8)$
Pe_10	Glare and specular reflection	$M_{DdPe}(27, 10)$
Pe_11	View	$M_{DdPe}(27, 11)$
Pe_17	Aesthetics	$M_{DdPe}(27, 17)$

Dd_28	**Reflectance of the interior**	
Pe_05	Illuminance level on a working plane	$M_{DdPe}(28, 5)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(28, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(28, 7)$
Pe_10	Glare and specular reflection	$M_{DdPe}(28, 10)$
Pe_17	Aesthetics	$M_{DdPe}(28, 17)$

(No *information variable* or *design decision variable* was associated with this *design decision variable.*)

Dd_29	**Function of artificial lighting**	
In_10	Daylight availability	$M_{InDd}(10, 29)$
Dd_01	Daylight priorities	$M_{DdDd}(1,29)$
Dd_08	Form of the building	$M_{DdDd}(8, 29)$

Dd_11	Glazing orientation and related glazing area	$M_{DdDd}(11, 29)$
Dd_15	Room depth	$M_{DdDd}(15, 29)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 29)$
Dd_28	Reflectance of the interior	$M_{DdDd}(28, 29)$
Pe_01	Energy consumption	$M_{DdPe}(29, 1)$
Pe_05	Illuminance level on a working plane	$M_{DdPe}(29, 5)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(29, 6)$
Pe_07	Average daylight factor (ADF)	$M_{DdPe}(29, 7)$
Pe_08	Colour properties	$M_{DdPe}(29, 8)$
Pe_09	Appearance / modelling	$M_{DdPe}(29, 9)$
Pe_10	Glare and specular reflection	$M_{DdPe}(29, 10)$

Dd_30	**Lighting system**	
In_06	Activities carried out	$M_{InDd}(6, 30)$
In_07	Visual tasks	$M_{InDd}(7, 30)$
Dd_21	Number and position of rooflights	$M_{DdDd}(21, 30)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 30)$
Dd_29	Function of artificial lighting	$M_{DdDd}(29, 30)$
Pe_01	Energy consumption	$M_{DdPe}(30, 1)$
Pe_05	Illuminance level on a working plane	$M_{DdPe}(30, 5)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(30, 6)$
Pe_16	Cost	$M_{DdPe}(30, 16)$

Dd_31	**Lamp types**	
In_06	Activities carried out	$M_{InDd}(6, 31)$
In_07	Visual tasks	$M_{InDd}(7, 31)$
In_15	Ambient climate	$M_{InDd}(15, 31)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 31)$
Dd_29	Function of artificial lighting	$M_{DdDd}(29, 31)$
Dd_32	Lighting luminaires	$M_{DdDd}(32, 31)$
Pe_01	Energy consumption	$M_{DdPe}(31, 1)$
Pe_08	Colour properties	$M_{DdPe}(31, 8)$
Pe_10	Glare and specular reflection	$M_{DdPe}(31, 10)$
Pe_16	Cost	$M_{DdPe}(31, 16)$

Dd_32	**Lighting luminaires**	
In_06	Activities carried out	$M_{InDd}(6, 32)$
Dd_31	Lamp types	$M_{DdDd}(31, 32)$
Pe_01	Energy consumption	$M_{DdPe}(32, 1)$
Pe_10	Glare and specular reflection	$M_{DdPe}(32, 10)$
Pe_16	Cost	$M_{DdPe}(32, 16)$

Dd_33	**Arrangement of the luminaires**	
Dd_21	Number and position of rooflights	$M_{DdDd}(21, 33)$
Dd_26	Window shapes and positions	$M_{DdDd}(26, 33)$
Dd_29	Function of artificial lighting	$M_{DdDd}(29, 33)$
Dd_34	Lighting control system	$M_{DdDd}(34, 33)$

Pe_01	Energy consumption	$M_{DdPe}(33, 1)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(33, 6)$
Pe_09	Appearance / modelling	$M_{DdPe}(33, 9)$
Pe_10	Glare and specular reflection	$M_{DdPe}(33,10)$
Pe_16	Cost	$M_{DdPe}(33, 16)$

(No *information variable* was associated with this *design decision variable.*)

Dd_34	**Lighting control system**	
In_08	Occupation patterns	$M_{InDd}(8, 34)$
Dd_29	Function of artificial lighting	$M_{DD}(29, 34)$
Dd_30	Lighting system	$M_{DD}(30, 34)$
Dd_31	Lamp types	$M_{DD}(31, 34)$
Dd_33	Arrangement of the luminaires	$M_{DD}(33, 34)$
Pe_01	Energy consumption	$M_{DdPe}(34, 1)$
Pe_06	Uniformity of illuminance level	$M_{DdPe}(34, 6)$
Pe_16	Cost	$M_{DdPe}(34, 16)$

(4) The design variables associated with *performance variables* for evaluation

In relation to the design decisions made, performance characteristics are examined in terms of the *performance variables* for evaluation (Pe). In other words, each of the *performance variables* can be associated with the *design decision variables* which represent the design decisions affecting a particular performance characteristic. Meanwhile, when the performance characteristics of the building being designed are examined, the conditions such as the client's requirements and constraints may need to be taken into account. Furthermore, it was considered that such examination may involve comparing the resulting performance characteristics with the *performance criteria* (Pc) which have established. The lists of the design variables associated with *performance variables* may, therefore, involve *design decision variables* (Dd), *information variable* (In) and *performance criteria* (Pc).

Pe_01	**Energy consumption**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 1)$
Dd_02	Sunshine priorities	$M_{DdPe}(2, 1)$
Dd_08	Form of the building	$M_{DdPe}(8, 1)$

Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 1)$
Dd_12	Construction type	$M_{DdPe}(12, 1)$
Dd_16	Use of natural ventilation	$M_{DdPe}(16, 1)$
Dd_17	Need for mechanical ventilation or air-conditioning	$M_{DdPe}(17, 1)$
Dd_20	Glazed area for rooflights	$M_{DdPe}(20, 1)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 1)$
Dd_27	Shading devices	$M_{DdPe}(27, 1)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 1)$
Dd_30	Lighting system	$M_{DdPe}(30, 1)$
Dd_31	Lamp types	$M_{DdPe}(31, 1)$
Dd_32	Lighting luminaires	$M_{DdPe}(32, 1)$
Dd_33	Arrangement of the luminaires	$M_{DdPe}(33, 1)$
Dd_34	Lighting control system	$M_{DdPe}(34, 1)$
In_04	Use of the building	$M_{InPe}(4, 1)$
In_06	Activities carried out	$M_{InPe}(6, 1)$
In_08	Occupation patterns	$M_{InPe}(8, 1)$
In_15	Ambient climate	$M_{InPe}(15, 1)$
Pc_01	Energy targets	

Pe_02	**Heat loss**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 2)$
Dd_08	Form of the building	$M_{DdPe}(8, 2)$
Dd_09	Use of rooflights	$M_{DdPe}(9, 2)$
Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 2)$
Dd_12	Construction type	$M_{DdPe}(12, 2)$
Dd_16	Use of natural ventilation	$M_{DdPe}(16, 2)$
Dd_17	Need for mechanical ventilation or air-conditioning	$M_{DdPe}(17, 2)$
Dd_18	Rooflight profiles	$M_{DdPe}(18, 2)$
Dd_19	Glazing materials for rooflights	$M_{DdPe}(19, 2)$
Dd_20	Glazed area for rooflights	$M_{DdPe}(20, 2)$
Dd_22	Area and dimension of individual rooflight	$M_{DdPe}(22, 2)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 2)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 3)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 2)$
Dd_27	Shading devices	$M_{DdPe}(27, 2)$
In_10	Daylight availability	$M_{InPe}(10, 2)$
In_11	Sunlight duration	$M_{InPe}(11, 2)$
In_15	Ambient climate	$M_{InPe}(15, 2)$

(No *performance criteria* (Pc) was associated with this *performance variable.*)

Pe_03	**Solar gain**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 3)$
Dd_02	Sunshine priorities	$M_{DdPe}(2, 3)$
Dd_06	Position of the building on the site	$M_{DdPe}(6, 3)$
Dd_07	Orientation of the building	$M_{DdPe}(7, 3)$
Dd_08	Form of the building	$M_{DdPe}(8, 3)$
Dd_09	Use of rooflights	$M_{DdPe}(9, 3)$

Dd_10	Roof shape	$M_{DdPe}(10, 3)$
Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 3)$
Dd_14	Accommodation plan	$M_{DdPe}(14, 3)$
Dd_18	Rooflight profiles	$M_{DdPe}(18, 3)$
Dd_19	Glazing materials for rooflights	$M_{DdPe}(19, 3)$
Dd_20	Glazed area for rooflights	$M_{DdPe}(20, 3)$
Dd_22	Area and dimension of individual rooflight	$M_{DdPe}(22, 3)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 3)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 3)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 3)$
Dd_27	Shading devices	$M_{DdPe}(27, 3)$
In_10	Daylight availability	$M_{InPe}(10, 3)$
In_11	Sunlight duration	$M_{InPe}(11, 3)$
Pc_04	Air qualities required	

Pe_04	**Ventilation performance**	
Dd_26	Window shapes and positions	$M_{DdPe}(26, 4)$
Dd_27	Shading devices	$M_{DdPe}(27, 4)$
Pc_04	Air qualities required	

(No *information variable* (In) was associated with this *performance variable.*)

Pe_05	**Illuminance level on a working plane**	
Dd_13	Functional connections	$M_{DdPe}(13, 5)$
Dd_14	Accommodation plan	$M_{DdPe}(14, 5)$
Dd_28	Reflectance of the interior	$M_{DdPe}(28, 5)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 5)$
Dd_30	Lighting system	$M_{DdPe}(30, 5)$
Pc_05	Illuminance level required	

(No *information variable* (In) was associated with this *performance variable.*)

Pe_06	**Uniformity of illuminance level**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 6)$
Dd_09	Use of rooflights	$M_{DdPe}(9, 6)$
Dd_21	Number and position of rooflights	$M_{DdPe}(21, 6)$
Dd_22	Area and dimension of individual rooflight	$M_{DdPe}(22, 6)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 6)$
Dd_27	Shading devices	$M_{DdPe}(27, 6)$
Dd_28	Reflectance of the interior	$M_{DdPe}(28, 6)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 6)$
Dd_30	Lighting system	$M_{DdPe}(30, 6)$
Dd_33	Arrangement of the luminaires	$M_{DdPe}(33, 6)$
Dd_34	Lighting control system	$M_{DdPe}(34, 6)$
Pc_06	Uniformity required	

(No *information variable* (In) was associated with this *performance variable.*)

Pe_07	**Average daylight factor (ADF)**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 7)$
Dd_06	Position of the building on the site	$M_{DdPe}(6, 7)$
Dd_07	Orientation of the building	$M_{DdPe}(8, 7)$
Dd_08	Form of the building	$M_{DdPe}(8, 8)$
Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 7)$
Dd_14	Accommodation plan	$M_{DdPe}(14, 7)$
Dd_15	Room depth	$M_{DdPe}(15, 7)$
Dd_18	Rooflight profiles	$M_{DdPe}(18, 7)$
Dd_19	Glazing materials for rooflights	$M_{DdPe}(19, 7)$
Dd_20	Glazed area for rooflights	$M_{DdPe}(20, 7)$
Dd_22	Area and dimension of individual rooflight	$M_{DdPe}(22, 7)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 7)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 7)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 7)$
Dd_27	Shading devices	$M_{DdPe}(27, 7)$
Dd_28	Reflectance of the interior	$M_{DdPe}(28, 7)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 7)$
In_05	Accommodation	$M_{InPe}(5, 7)$
In_10	Daylight availability	$M_{InPe}(10, 7)$
Pc_07	Target average daylight factor	

Pe_08	**Colour properties**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 8)$
Dd_14	Accommodation plan	$M_{DdPe}(14, 8)$
Dd_19	Glazing materials for rooflights	$M_{DdPe}(19, 8)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 8)$
Dd_27	Shading devices	$M_{DdPe}(27, 8)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 8)$
Dd_31	Lamp types	$M_{DdPe}(31, 8)$
Pc_08	Colour properties required	

(No *information variable* (In) was associated with this *performance variable.*)

Pe_09	**Appearance / modelling**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 9)$
Dd_09	Use of rooflights	$M_{DdPe}(9, 9)$
Dd_14	Accommodation plan	$M_{DdPe}(14, 9)$
Dd_18	Rooflight profiles	$M_{DdPe}(18, 9)$
Dd_23	Primary function of side windows	$M_{DdPe}(23, 9)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 9)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 9)$
Dd_33	Arrangement of the luminaires	$M_{DdPe}(33, 9)$

(No *information variable* (In) or *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_10	**Glare and specular reflection**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 10)$
Dd_02	Sunshine priorities	$M_{DdPe}(2, 10)$
Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 10)$
Dd_19	Glazing materials for rooflights	$M_{DdPe}(19, 10)$
Dd_21	Number and position of rooflights	$M_{DdPe}(21, 10)$
Dd_22	Area and dimension of individual rooflight	$M_{DdPe}(22, 10)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 10)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 10)$
Dd_27	Shading devices	$M_{DdPe}(27, 10)$
Dd_28	Reflectance of the interior	$M_{DdPe}(28, 10)$
Dd_29	Function of artificial lighting	$M_{DdPe}(29, 10)$
Dd_31	Lamp types	$M_{DdPe}(31, 10)$
Dd_32	Lighting luminaires	$M_{DdPe}(32, 10)$
Dd_33	Arrangement of the luminaires	$M_{DdPe}(33, 10)$
In_06	Activities carried out	$M_{InPe}(6, 10)$

(No *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_11	**View**	
Dd_01	Daylight priorities	$M_{DdPe}(1, 11)$
Dd_03	View priorities	$M_{DdPe}(3, 11)$
Dd_06	Position of the building on the site	$M_{DdPe}(6, 11)$
Dd_07	Orientation of the building	$M_{DdPe}(7, 11)$
Dd_15	Room depth	$M_{DdPe}(15, 11)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 11)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 11)$
Dd_27	Shading devices	$M_{DdPe}(27, 11)$
In_12	View	$M_{InPe}(12, 11)$

(No *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_12	**Privacy**	
Dd_03	View priorities	$M_{DdPe}(3, 12)$
Dd_06	Position of the building on the site	$M_{DdPe}(6, 12)$
Dd_07	Orientation of the building	$M_{DdPe}(7, 12)$
Dd_08	Form of the building	$M_{DdPe}(8, 12)$
Dd_11	Glazing orientation and related glazing area	$M_{DdPe}(11, 12)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 12)$
In_09	Boundaries	$M_{InPe}(9, 12)$

(No *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_13	**Noise level within the building**	
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 13)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 13)$
In_13	Noise sources	$M_{InPe}(13, 13)$
Pc_13	Noise insulation level required	

Pe_14	**Structure**	
Dd_21	Number and position of rooflights	$M_{DdPe}(21, 14)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 14)$

(No *information variable* (In) or *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_15	**Overshadowing**	
Dd_06	Position of the building on the site	$M_{DdPe}(6, 15)$
Dd_07	Orientation of the building	$M_{DdPe}(7, 15)$
Dd_08	Form of the building	$M_{DdPe}(8, 15)$
In_09	Boundaries	$M_{InPe}(9, 15)$
In_10	Daylight availability	$M_{InPe}(10, 15)$

(No *performance criterion* (Pc) was associated with this *performance variable.*)

Pe_16	**Cost**	
Dd_08	Form of the building	$M_{DdPe}(8, 16)$
Dd_30	Lighting system	$M_{DdPe}(30, 16)$
Dd_31	Lamp types	$M_{DdPe}(31, 16)$
Dd_32	Lighting luminaires	$M_{DdPe}(32, 16)$
Dd_33	Arrangement of the luminaires	$M_{DdPe}(33, 16)$
Dd_34	Lighting control system	$M_{DdPe}(34, 16)$
Pc_16	Cost range criteria (construction)	

(No *information variable* (In) was associated with this *performance variable.*)

Pe_17	**Aesthetics**	
Dd_08	Form of the building	$M_{DdPe}(8, 17)$
Dd_23	Primary function of side windows	$M_{DdPe}(23, 17)$
Dd_24	Glazing material for side windows	$M_{DdPe}(24, 17)$
Dd_25	Glazed area for side windows	$M_{DdPe}(25, 17)$
Dd_26	Window shapes and positions	$M_{DdPe}(26, 17)$
Dd_27	Shading devices	$M_{DdPe}(27, 17)$
Dd_28	Reflectance of the interior	$M_{DdPe}(28, 17)$

(No *information variable* (In) or *performance criterion* (Pc) was associated with this *performance variable.*)

Appendix F

Appendix F

BASIC GRAPH THEORY, MATRIX REPRESENTATION OF GRAPHS, AND A STRUCTURAL MODEL OF THE DESIGN DECISION-MAKING PROCESS

A *structural model* is a model describing the structure of a system, i.e. how the whole system is composed from its sub-systems, or components, inter-related with each other. Structural models are qualitative since they normally describe only the existence of relationships between their sub-systems, and, because of their simplicity, they are often capable of expressing the structural properties of complicated systems. A structural model can be described using a graph consisting of the nodes describing attributes of the structure, and the paths between them, which represent its sub-systems and their relationships, respectively. Corresponding to such a graph, a matrix can also be used to describe a structural model. Since logical operations can be applied to matrices, a mathematical model of the system could be developed.

In Section 4.3 of Chapter 4, a structural model of the building design process was developed by describing the relationships between *design variables*, the inter-relationships between design decisions in particular. In order to supplement the discussion in Section 4.3, this appendix provides some basic notions about the graph theory and the matrix representation of graphs, regarding the development of the structural model.

F.1 Graph Theory

F.1.1 Directed graph

A set of points and the branches connecting them, may be considered to constitute a *graph*. In the diagram shown in Figure F.1, for example, the points (represented by *A*, *B*, *C* etc.), which may also be called *nodes* or *vertices*, are connected by directed lines with specific orientations, that may also be referred to as *arcs*, *directed branches*, or *directed edges*.

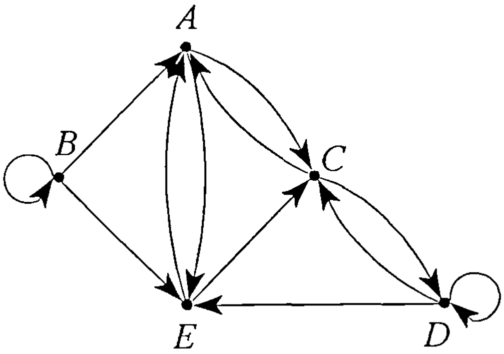


Figure F.1 An example of a directed graph

Graphs can be used to represent structures of diverse natures, such as a network of roads or streets, an electrical circuit, or the operations of assembling and dismantling a technological system. From a set of separate objects involved in a system, and laws of correspondence between these objects, a graph can be drawn which describes the structure of the system. But, the graph in each case must not be confused with the concept associated with it; it is merely the structure, in which the use of nodes and arcs provides a useful representation of certain properties which are of interest [Kaufmann, 1967].

Directed graphs

Directed graphs consist of *directed branches*, or *arcs*, interconnected at nodes. Two nodes are *adjacent*, or *connected*, if there is an arc between them in either direction.

Partial graph and *Sub-graph*

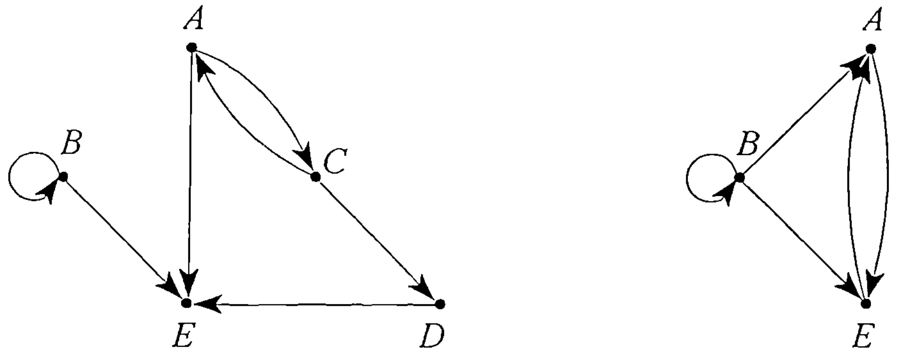
If one or more arcs are omitted from a graph, a *partial graph* is formed from the original graph. If one or more nodes are omitted, together with the arcs to and from these points, the remaining portion of the graph is a *sub-graph* of the reference graph. Figure F.2 (a) and (b) illustrate a *partial graph* and a *sub-graph* of the one shown in Figure F.1, respectively.

Path, *Circuit*, and *Length of a path*

These notions are associated with a directed graph. A *path* is a sequence of at least two connected arcs which give access from one node to another, taking account of their directions. A path can be described by a list of the arcs, e.g. (b, d, f), or nodes, e.g. (B, A, C, D), which it contains (see Figure F.3 (a)). A path is *elementary*, or *open*, if it does not make use of the same node twice (e.g. path (b, d, f) in Figure F.3 (a)). A path in which the initial and final nodes coincide is called *circuit* (e.g. path (d, f, i, k) in Figure F.3 (b), which can be also described as (A, C, D, E, A)). If a circuit is composed of a single arc and a single node, it is a *loop* (e.g. arc a and h in Figure F.3 (c)). The *length* of a path is the number of arcs contained in the sequence. In Figure F.3 (a), for instance, the length of the path (b, d, f) is 3.

Strongly connected graph

A directed graph is said to be *strongly connected*, if, for every pair of distinct nodes (X, Y), there exists at least a path from X to Y, as well as one from Y to X. In other words, every node within a strongly connected graph can be reached from any other nodes through a path. The graph shown in Figure F.4 (a) is strongly connected, whereas that in Figure F.4 (b) is not strongly connected.



(a) partial graph (b) subgraph

Figure F.2 Partial graph and subgraph of Figure F.1

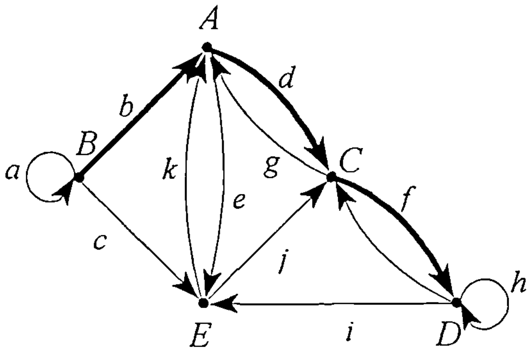


Figure F.3 (a) elementary path (length = 3)

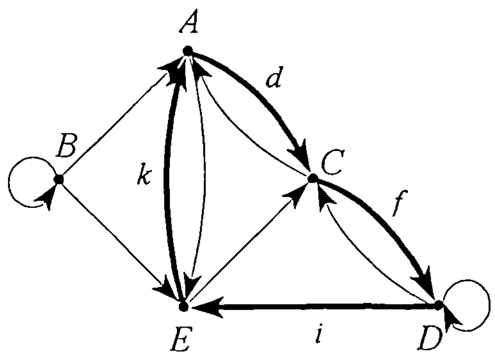


Figure F.3 (b) Circuit

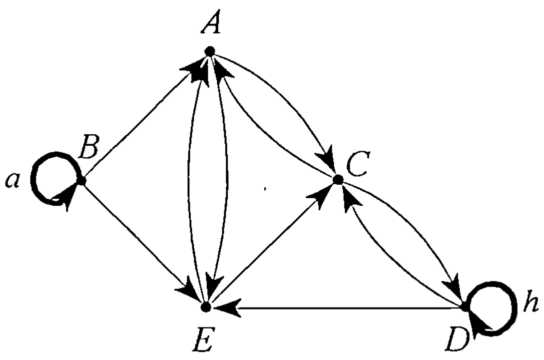


Figure F.3 (c) Loops

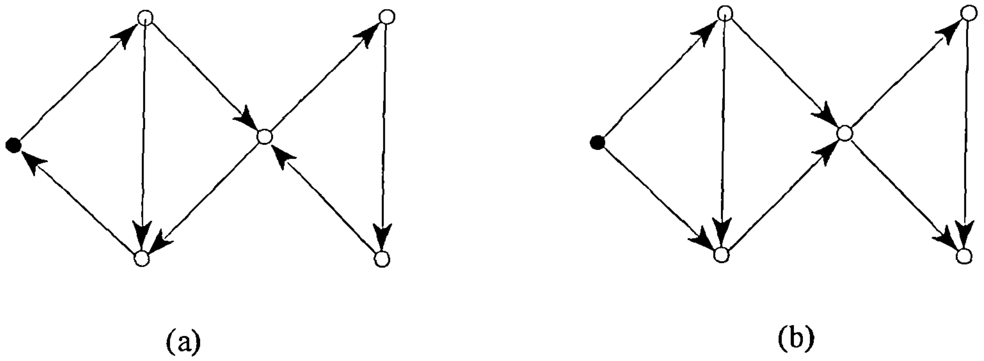


Figure F.4 Graph (a) is a strongly connected graph, but (b) is not.

F.1.2 Undirected graph

Undirected graph and *links*

It can be said that a *link* exists between two nodes X and Y if there is an arc from X to Y and/or from Y to X. In other words, a *link* is established between a pair of nodes joined by at least one arc regardless of its direction. In this case, these nodes may be inter-connected by undirected lines, which may be called *edges*, as shown in Figure F.5. Such a graph is called an *undirected graph.*

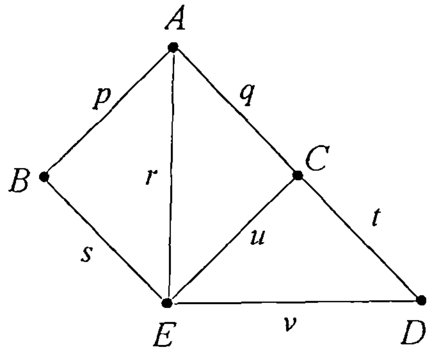
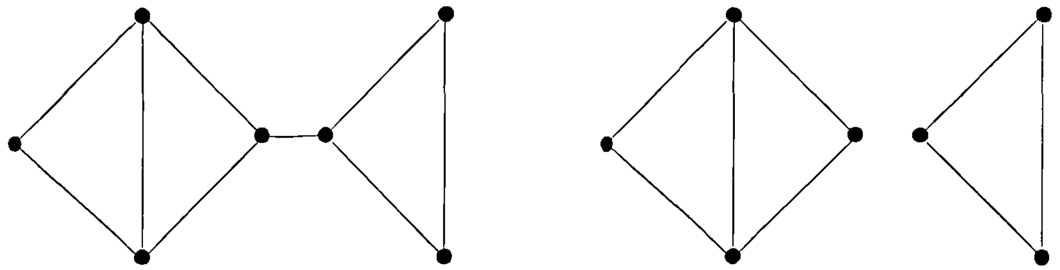


Figure F.5 Undirected graph

Chain, *Cycle*, and a *Connected graph*

A *chain* is a series of consecutive links, e.g. (*p*, *q*, *t*), in Figure F.5 is a chain between the nodes *B* and *D*, which can be also described as (*B*, *A*, *C*, *D*) in terms of the nodes involved. A *cycle* is a closed chain, i.e. a finite chain which leaves and ends at the same node. In Figure F.5, for instance, a chain (*q*, *t*, *v*, *r*) is a cycle. If each pair of distinct nodes is connected by at least one chain, the graph is called a *connected graph* (see Figure F.6). Chains and cycles are often related to undirected graphs, while paths and circuits are usually associated with directed graphs.



(a) Connected graph (b) Unconnected graph

Figure F.6 Connected graph and unconnected graph

Further explanation about graph theory in mathematical terms can be found in the following text books:

Kaufmann, A., "*GRAPHS, DYNAMIC PROGRAMMING, AND FINITE GAMES*" (Academic Press, 1967), Chapter I and IV;

Busacker, R.G. and Saaty, T.L., "*FINITE GRAPHS AND NETWORKS: An Introduction with Applications*" (McGraw-Hill, 1965), Chapter 1 and 2.

F.2 Matrix Representation of Graphs

Matrices can be used to represent the relations between the nodes and branches of a graph. The matrix representation of directed and undirected graphs have both aesthetic and utilitarian value. It is possible to deduce incidence relations and circuits by matrix theorems and manipulations. Although various matrices can be defined to represent a graph, only the *adjacency matrix* and *reachability matrix* associated with it are explained here. Then the development of a structural model using these matrices is demonstrated with an example.

F.2.1 Adjacency matrix and reachability matrix

Adjacency matrix and *the Boolean algebra*

Given a directed graph containing *n* nodes $X_1, X_2, ..., X_n$, a square matrix can be formed whose element m_{ij} has a value of "1" if there is an arc from the node X_i to X_j, otherwise it has "0". This matrix is called an *adjacency matrix,* which may also be called a *node matrix* or *associated matrix,* and is represented by the sign [*A*]. Table F.1 (a) shows the adjacency matrix [*A*] representing the graph illustrated in Figure F.7. If the element m_{ij} of the adjacency matrix [*A*] has a value of "1", it means that there is an arc from the node X_i to X_j.

The elements of an adjacency matrix can be considered to represent a truth value, where a value of "1" says "yes" (there is a connection), and a value of "0" says "no" (there is no connection). In this context the sum and product (multiplication) of its elements can be understood in terms of "yes" and "no" propositions, i.e. the *Boolean algebra* [Henley and Williams, 1973, pp.265]. The sum and multiplication in accordance with the Boolean algebra are as follows:

Sum:

$0 + 0 = 0$

$0 + 1 = 1 + 0 = 1$

$1 + 1 = 1$

Multiplication: $0 * 0 = 0$
$0 * 1 = 1 * 0 = 0$
$1 * 1 = 1.$

The matrices the product and sum of which follow the Boolean algebra may be called *Boolean matrices*. In the following part of this Appendix, assume that all matrices are Boolean matrices, and their sum and product are carried out in accordance with the Boolean algebra.

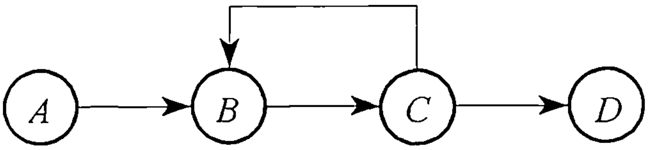


Figure F.7 A cyclic graph corresponding the adjacency matrix of Table F.1.
[Henly and Williams, 1973, pp.179]

Table F.1 The adjacency matrix [A] representing the graph shown in Figure F.7, and its 2nd and 3rd powers.

	A	*B*	*C*	*D*
A	0	1	0	0
B	0	0	1	0
C	0	1	0	1
D	0	0	0	0

[A]

	A	*B*	*C*	*D*
A	0	0	1	0
B	0	1	0	1
C	0	0	1	0
D	0	0	0	0

$[A]^2$

	A	*B*	*C*	*D*
A	0	1	0	1
B	0	0	1	0
C	0	1	0	1
D	0	0	0	0

$[A]^3$

An adjacency matrix has an interesting property: its *r*th Boolean power, $[A]^r$, shows the paths of length *r* within the corresponding graph. Considering the graph in Figure F.7, for example, the paths of length 2 and 3 can be identified by calculating the 2nd and 3rd powers of the corresponding adjacency matrix which is shown in Table F.1 (a). Applying the Boolean operation to the adjacency matrix $[A]$, its 2nd and 3rd powers are obtained as shown in Table F.1 (b), and (c) respectively. Here, $[A]^2$ indicates the paths of length 2 within the graph, i.e. (A, B, C), (B, C, B), (B, C, D) and (C, B, C). Similarly $[A]^3$ shows the paths of length 3, such as (A, B, C, B) and (B, C, B, C). As the number of power n becomes higher, $[A]^n$ will eventually no longer disclose any new paths, since all paths of length n have been found and the same circuits are simply traversed for more than n. In this example, the 4th power of the adjacency matrix, $[A]^4$, for instance, will be identical to $[A]^2$. For a graph which contains no circuit in it, all the elements of the nth power of its adjacency matrix have "0" when n exceeds the longest path in the graph.

Reachability matrix

Let us consider a matrix $[M]=[I]+[A]$, where $[I]$ is a unit matrix which has a value of "1" for its diagonal elements and "0" for the others, and $[A]$ is an adjacency matrix. Since these matrices are Boolean, calculating:

$$[M]^2 = ([I]+[A])^2 = [I] + [A] + [A]^2$$

$$[M]^n = ([I]+[A])^n = [I] + [A] + [A]^2 + ... + [A]^n .$$

This $[M]^n$ matrix will have a value of "1" for its element $m^{(n)}_{ij}$ if there is a path of length less than or equal to n from the node X_i to X_j, otherwise it will have a value of "0".

Considering a graph containing N nodes, every elementary path (i.e. every path which does not make use of the same node twice) has a length less than or equal to N-1. Since every path is the aggregate of elementary paths, the matrix $[M]^{N-1}$ implies all the paths (elementary paths or otherwise) within the corresponding graph, and the matrix $[M]^n$ will no longer change for any natural number n greater than N-1. Such a matrix as $[M]^{N\text{-}1}$ is called the *reachability matrix* of [A], and may be denoted by $[M_R]$, and indicates whether a path exist from each of the nodes to another. If a graph is strongly connected, i.e. if a path can be established from any node to every one of the others, the reachability matrix will, therefore, have a value of "1" for each of its elements.

F.2.2 The Matrices and a Structural Model of a System

A structural model based upon the reachability matrix

By studying a reachability matrix, the structure of the graph, such as circuits and the hierarchy of its nodes, can be understood. Let us consider the directed graph illustrated in Figure F.8, for example. The adjacency matrix [A] representing this graph is shown in Table F.2, and its reachability matrix $[M_R]$ is in Table F.3.

Table F.2 The adjacency matrix of the graph shown in Figure F8.

	X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*	*X8*
X1					1	1		
X2			1					1
X3								1
X4	1	1						
X5								
X6	1		1					
X7				1				
X8		1						

Table F.3 The reachability matrix of the graph shown in Figure F8.

	X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*	*X8*
X1	1	1	1		1	1		1
X2		1	1					1
X3		1	1					1
X4	1	1	1	1	1	1		1
X5					1			
X6	1	1	1		1	1		1
X7	1	1	1	1	1	1	1	1
X8		1	1					1

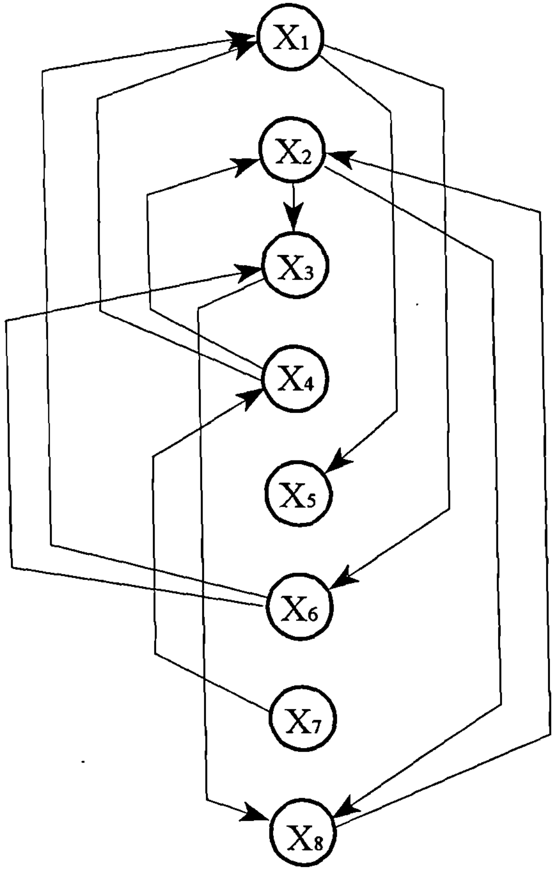


Figure F.8 A directed graph corresponding the adjacency matrix in Table F.2. [Terano,1985, pp37]

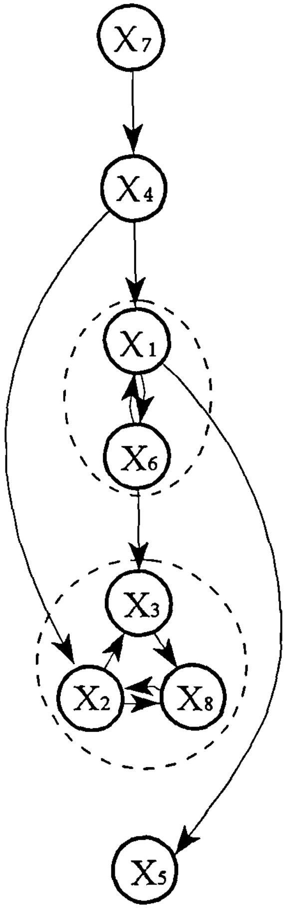


Figure F.9 The hierarchy of Figure F.8 [Terano, 1985, pp.39]

Table F.4 Studying the reachability matrix to order the vertices.

(a)

	X_1	X_2	X_3	X_4	X_6	X_8
X_1	1	1	1		1	1
X_2		1	1			1
X_3		1	1			1
X_4	1	1	1	1	1	1
X_6	1	1	1		1	1
X_8		1	1			1

(b)

	X_1	X_2	X_3	X_6	X_8
X_1	1	1	1	1	1
X_2		1	1		1
X_3		1	1		1
X_6	1	1	1	1	1
X_8		1	1		1

(c)

	X_2	X_3	X_8
X_2	1	1	1
X_3	1	1	1
X_8	1	1	1

Studying this reachability matrix, it is found, initially, that all the elements in the row corresponding to the node X_7 have values of “1”. This means that starting from the node X_7 any other nodes can be reached through paths: the node X_7 is at the primary position of the graph. All the elements in row X_5, on the other hand, have “0” except its diagonal element m_{55}, which has a value of "1". This suggests that the node X_5 has no path to any other nodes, i.e. it can only be at the end of the paths involving it. By eliminating the rows and columns associated with nodes X_7 and X_5 from the original reachability matrix, the matrix shown in Table F.4 (a) is obtained which represents the sub-graph containing the remaining nodes. This matrix shows the node X_4 to be at the primary position within the sub-graph. If the row and column associated with the node X_4 are eliminated, the resulting matrix, shown in Table F.4 (b), suggests that the nodes X_1 and X_6 occupy primary positions within the sub-graph which consists of the nodes X_1, X_2, X_3, X_6 and X_8. Then, by eliminating the rows and columns associated with the nodes X_1 and X_6, the matrix shown in Table F.4 (c) is obtained which implies that the sub-graph comprising the nodes X_2, X_3 and X_8 is strongly connected. Finally, the hierarchical structure of the graph can emerge as illustrated in Figure F.9, by grouping and sorting the nodes according to the positions within the graph and sub-graphs as described above. Here, the nodes encircled by dotted lines are considered to be strongly connected themselves, and should stay together in the same level of the hierarchy. This diagram indicates that a node can be reached from those within the higher levels of the hierarchy, but cannot be reached from those within the lower levels. Depending upon what the system is, this may be interpreted that the nodes in the higher levels of the hierarchy could affect those in the lower levels.

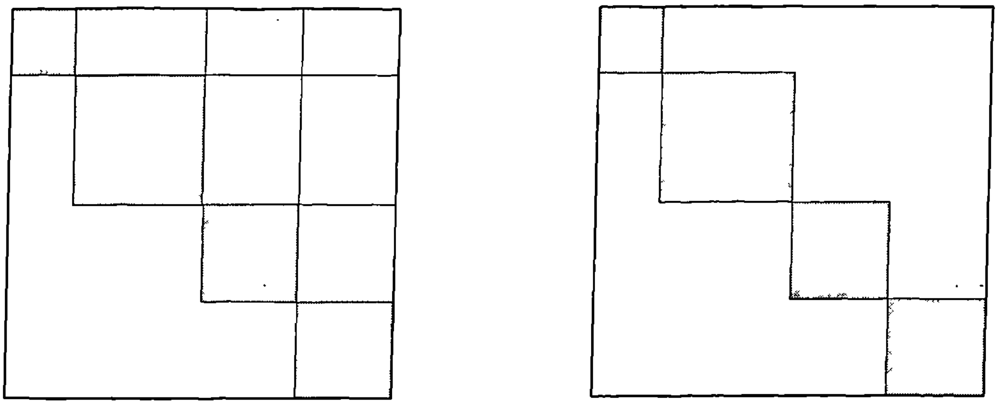
The adjacency matrix and the outline of a structural model

A group of the nodes which are strongly connected (e.g. X_2, X_3 and X_8 in Figure F.9) can be considered to constitute a *subsystem* of the whole system. By interchanging the rows and columns of the adjacency matrix, such a subsystem can be described as a ***block***, which is the elements split into rectangular blocks by one or more horizontal and vertical partitions (Figure F.10). If all the blocks on the main diagonal are square, and all the blocks on either side of the main diagonal contain only a value of "0", it is called a "*block-triangular matrix*" (Figure F.11 (a)). If all the blocks on both sides of the main diagonal are zero, it is called a *block-diagonal matrix* (Figure F.11 (b)). If the adjacency matrix can be made a block-triangular matrix, the system has a hierarchical structure comprising the subsystems represented by the blocks on the main diagonal, since there are some connections in a single direction between these subsystems. But, the system can consist of the subsystems which are independent from each other, if the adjacency matrix can be a block-diagonal matrix, because no paths connecting them exist.

Let us consider the graph shown in Figure F.9, for example. The adjacency matrix, as well as the corresponding reachability matrix, can be made *block-triangular matrices*, as shown in Table F.5 (a) and (b), respectively, by interchanging the rows and columns taking account of the hierarchy of the nodes as well as the strongly connected nodes, i.e. X_1 and X_6, and X_2, X_3 and X_8. These matrices can describe the hierarchical structure of the nodes, as well as the subsystems consisting of those strongly connected.

$$\begin{array}{|c|cc|ccc|}
\hline
a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\
\hline
a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\
a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\
\hline
a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\
a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\
a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \\
\hline
\end{array}$$

Figure F.10 An example of a block matrix



(a) Block-triangular matrix

(b) Block-diagonal matrix

☐ : high density of a value "1"

☐ : low density of a value "1"

☐ : all elements have a value of "0"

Figure F.11 Adjacency matrix and a structure of the system:
(a) block-triangular matrix, which represents the subsystems forming a hierarchical structure; and
(b) block-diagonal matrix, which represents the subsystems which are independent from each other.

Table F.5 The block-triangular adjacency matrix, and reachability matrix, representing the graph shown in Figure F.8 and F.9.

	X_7	X_4	X_1	X_6	X_2	X_3	X_8	X_5
X_7		1						
X_4			1		1			
X_1				1				1
X_6			1			1		
X_3							1	
X_2						1	1	
X_8					1			
X_5								

(a) Adjacency matrix

	X_7	X_4	X_1	X_6	X_2	X_3	X_8	X_5
X_7	1	1	1	1	1	1	1	1
X_4		1	1	1	1	1	1	1
X_1			1	1	1	1	1	1
X_6			1	1	1	1	1	1
X_3					1	1	1	
X_2					1	1	1	
X_8					1	1	1	
X_5								1

(b) Reachability matrix

For further explanation about the matrix representation, the following books can be referred to:

Kaufmann, A., *"GRAPHS, DYNAMIC PROGRAMMING, AND FINITE GAMES"* (Academic Press, 1967), Chapter IV;

Henley, E.J., and Williams, R.A., "*GRAPH THEORY IN MODERN ENGINEERING: Computer Aided Design, Control, Optimization, Reliability Analysis*" (Academic Press, 1973), Chapter 10.

More explanation about the structural models in relation to the matrix representation should be found in text books of systems engineering. The following book which is written in Japanese was used::

Terano, "*Introduction to Systems Engineering*" (Kyoritsu, 1985), Chapter 2 and 7.

F.3 A Structural Model of the *Design Decision Variables* and the Sequence of the Design Decision-Making

In Chapter 4, the *design decisions variables* were defined. Studying the itemised knowledge described in Appendix D, the relationships between these *variables* were examined and described in the matrix M_{DdDd}, which is shown in Table F.6 in this Appendix, as well as in Section 4.3 of Chapter 4. For the convenience of the examination, the reference numbers, from 1 to 34, were assigned to the rows and columns in accordance with the *design decision variables*. These numbers will be used to specify particular rows and columns of the matrices.

Table F.6 The adjacency matrix associated with *the design decision variables*

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		d01	d02	d03	d04	d05	d06	d07	d08	d09	d10	d11	d12	d13	d14	d15	d16	d17	d18	d19	d20	d21	d22	d23	d24	d25	d26	d27	d28	d29	d30	d31	d32	d33	d34
1	Dd_01						1	1	1	1		1			1	1					1			1		1	1	1		1					
2	Dd_02			1			1	1	1	1		1			1				1	1					1		1	1							
3	Dd_03		1					1				1												1		1	1	1							
4	Dd_04								1							1	1	1							1		1								
5	Dd_05	1	1		1							1					1	1							1	1	1								
6	Dd_06																																		
7	Dd_07											1																							
8	Dd_08						1			1	1	1							1		1			1	1	1	1			1					
9	Dd_09								1		1								1									1							
10	Dd_10																		1																
11	Dd_11																						1		1	1		1		1					
12	Dd_12																					1				1	1								
13	Dd_13														1																				
14	Dd_14															1										1									
15	Dd_15														1		1									1	1			1					
16	Dd_16																	1							1		1	1							
17	Dd_17																																		
18	Dd_18																						1					1							
19	Dd_19																				1														
20	Dd_20															1				1			1												
21	Dd_21															1							1					1			1			1	
22	Dd_22															1												1							
23	Dd_23																								1	1	1								
24	Dd_24																									1	1	1							
25	Dd_25															1									1										
26	Dd_26															1												1		1	1	1		1	
27	Dd_27																				1					1									
28	Dd_28															1					1					1				1					
29	Dd_29																														1	1		1	1
30	Dd_30																																		1
31	Dd_31																																1		1
32	Dd_32																															1			
33	Dd_33																																		1
34	Dd_34																																	1	

The matrix M_{DdDd} is the adjacency matrix regarding the graph where the *design decision variables* and their relationships are represented by the nodes and arcs, respectively. Therefore, a structural model of the *design decisions variables* relationships may be developed by examining the reachability matrix derived from the M_{DdDd} matrix. It is understood that, since this structural model represents the inter-dependency between the design decisions, an adequate sequence of design decision-making may be defined based upon it.

The structural model of the *design decision variables* was developed in two phases as follows:

Phase 1: Studying the reachability matrix:
The *design decision variables* were classified into ordered "*Classes*" by studying the reachability matrix; and then

Phase 2: Developing a brief structure of the *design decision variables*:
Based upon these "*Classes*" established in Phase 1, a hierarchical structural model of the *design decision variables* was developed as a series of "*Design Steps*", by reducing the number of the relationships to be considered, i.e. by considering the relationships between two design decisions belonging to the different *Classes* which are adjacent to each other.

Phase 1 and 2 are explained in detail in the following Section F.3.1 and F.3.2, respectively.

F.3.1 Phase 1: Studying the reachability matrix

In the example of examining a reachability matrix explained in Section F.2.2 of this Appendix, the rows were sought which have a value of "1" for all of their elements. This time, however, the examination was carried out by seeking the columns, rather than rows, which have a value of "0" for each of their elements except the diagonal ones. This can be considered, in terms of the graph theory, as the search of the nodes which cannot be reached from the others within the as the search of the nodes which cannot be reached from the others within the graph or sub-graphs associated with the matrices being examined. In other words, the design decisions were sought which cannot be affected by the other decisions within the sets of the design decisions associated with the matrices. Meanwhile, a strongly connected sub-graph, which is represented by a block element on the main diagonal filled with a value of "1" within the reachability matrix, is considered to form a subsystem within the whole system of the *design decision variables*. Identifying such subsystems was also a part of this phase.

Table F.7 The reachability matrix associated with the *design decision variables*

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	Dd_01	1					1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
2	Dd_02		1	1			1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
3	Dd_03		1	1			1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
4	Dd_04				1		1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
5	Dd_05	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
6	Dd_06						1																												
7	Dd_07							1				1			1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
8	Dd_08						1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
9	Dd_09						1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
10	Dd_10										1				1	1	1	1	1	1	1		1		1	1	1	1		1	1	1	1	1	1
11	Dd_11											1			1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
12	Dd_12												1		1	1	1	1		1	1	1	1		1	1	1	1		1	1	1	1	1	1
13	Dd_13													1	1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
14	Dd_14														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
15	Dd_15														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
16	Dd_16														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
17	Dd_17																	1																	
18	Dd_18														1	1	1	1	1	1	1		1		1	1	1	1		1	1	1	1	1	1
19	Dd_19														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
20	Dd_20														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
21	Dd_21														1	1	1	1		1	1	1	1		1	1	1	1		1	1	1	1	1	1
22	Dd_22														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
23	Dd_23														1	1	1	1		1	1		1	1	1	1	1	1		1	1	1	1	1	1
24	Dd_24														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
25	Dd_25														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
26	Dd_26														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
27	Dd_27														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
28	Dd_28														1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1	1
29	Dd_29																													1	1	1	1	1	1
30	Dd_30																														1			1	1
31	Dd_31																															1	1	1	1
32	Dd_32																															1	1	1	1
33	Dd_33																																	1	1
34	Dd_34																																	1	1

The reachability matrix calculated from the M_{DdDd} matrix (the adjacency matrix concerning the *design decision variables*) is shown in Table F.7. The examination was carried out in 8 steps as explained below:

[Step 1] Within the reachability matrix, it was recognised that the columns (5), (12), (13) and (28) have a value of "1" only in their diagonal elements (see Table F.8 (a)). This means that these design decisions cannot be affected by the other design decisions, although they may affect the others. These design decisions were categorised as *Class* 1 (Table F.9). Having eliminated the rows and columns associated with these *design decision variables*, the matrix shown in Table F.8 (b) was obtained.

Table F.8 (a) Study of the reachability matrix (Step 1)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	Dd_01	1					1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
2	Dd_02		1	1			1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
3	Dd_03		1	1			1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
4	Dd_04				1		1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
5	Dd_05	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
6	Dd_06						1																												
7	Dd_07							1				1			1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
8	Dd_08						1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
9	Dd_09						1		1	1	1	1			1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1
10	Dd_10										1				1	1	1	1	1	1	1		1		1	1	1	1		1	1	1	1	1	1
11	Dd_11											1			1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
12	Dd_12												1		1	1	1	1		1	1	1	1		1	1	1	1		1	1	1	1	1	1
13	Dd_13													1	1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
14	Dd_14														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
15	Dd_15														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
16	Dd_16														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
17	Dd_17																	1																	
18	Dd_18														1	1	1	1	1	1	1		1		1	1	1	1		1	1	1	1	1	1
19	Dd_19														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
20	Dd_20														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
21	Dd_21														1	1	1	1		1	1	1	1		1	1	1	1		1	1	1	1	1	1
22	Dd_22														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
23	Dd_23														1	1	1	1		1	1		1	1	1	1	1	1		1	1	1	1	1	1
24	Dd_24														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
25	Dd_25														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
26	Dd_26														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
27	Dd_27														1	1	1	1		1	1		1		1	1	1	1		1	1	1	1	1	1
28	Dd_28														1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1	1
29	Dd_29																													1	1	1	1	1	1
30	Dd_30																														1			1	1
31	Dd_31																															1	1	1	1
32	Dd_32																															1	1	1	1
33	Dd_33																																	1	1
34	Dd_34																																	1	1

Table F.8 (b) Study of the reachability matrix (Step 2)

		1	2	3	4	6	7	8	9	10	11	14	15	16	17	18	19	20	21	22	23	24	25	26	27	29	30	31	32	33	34
1	Dd_01	1				1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
2	Dd_02		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
3	Dd_03		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
4	Dd_04				1	1		1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
6	Dd_06					1																									
7	Dd_07						1				1	1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
8	Dd_08					1		1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
9	Dd_09					1		1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
10	Dd_10									1		1	1	1	1	1	1	1		1		1	1	1	1	1	1	1	1	1	1
11	Dd_11										1	1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
14	Dd_14											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
15	Dd_15											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
16	Dd_16											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
17	Dd_17														1																
18	Dd_18											1	1	1	1	1	1	1		1		1	1	1	1	1	1	1	1	1	1
19	Dd_19											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
20	Dd_20											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
21	Dd_21											1	1	1	1		1	1	1	1		1	1	1	1	1	1	1	1	1	1
22	Dd_22											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
23	Dd_23											1	1	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
25	Dd_25											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
26	Dd_26											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
27	Dd_27											1	1	1	1		1	1		1		1	1	1	1	1	1	1	1	1	1
29	Dd_29																									1	1	1	1	1	1
30	Dd_30																										1			1	1
31	Dd_31																											1	1	1	1
32	Dd_32																											1	1	1	1
33	Dd_33																													1	1
34	Dd_34																													1	1

[Step 2] Table F.8 (b) indicates that the design decision (2) and (3) are strongly connected. Having considered this, it was found that the design decision (1), (4), or (2) and (3) could not be affected by the other decisions associated with this matrix, since they have the value of "1" for only their diagonal elements (the diagonal block for (2) and (3)). These design decisions were categorised as *Class* 2 (see Table F.9). The rows and columns associated with them were eliminated, and as a result, the matrix shown in Table F.8 (c) was obtained.

Table F.8 (c) Study of the reachability matrix (Step 3)

		6	7	8	9	10	11	14	15	16	17	18	19	20	22	23	24	25	26	27	29	30	31	32	33	34
6	Dd_06	1																								
7	Dd_07		1				1	1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
8	Dd_08	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	Dd_09	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	Dd_10					1		1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
11	Dd_11						1	1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
14	Dd_14							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
15	Dd_15							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
16	Dd_16							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
17	Dd_17										1															
18	Dd_18							1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
19	Dd_19							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
20	Dd_20							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
22	Dd_22							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
23	Dd_23							1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
25	Dd_25							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
26	Dd_26							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
27	Dd_27							1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
29	Dd_29																				1	1	1	1	1	1
30	Dd_30																					1			1	1
31	Dd_31																						1	1	1	1
32	Dd_32																						1	1	1	1
33	Dd_33																								1	1
34	Dd_34																								1	1

<u>[Step 3]</u> Table F.8 (c) showed that the design decision (8) and (9) were strongly connected, and also that the design decision (7), as well as (8) and (9), could not be affected by the other design decisions associated with this matrix. These design decisions were classified as *Class* 3 (see Table F.9). Having eliminated the rows and columns associated with them, Table F.8 (d) was obtained.

Table F.8 (d) Study of the reachability matrix (Step 4)

		6	10	11	14	15	16	17	18	19	20	22	23	24	25	26	27	29	30	31	32	33	34
6	Dd_06	1																					
10	Dd_10		1		1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
11	Dd_11			1	1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
14	Dd_14				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
15	Dd_15				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
16	Dd_16				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
17	Dd_17							1															
18	Dd_18				1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
19	Dd_19				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
20	Dd_20				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
22	Dd_22				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
23	Dd_23				1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
25	Dd_25				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
26	Dd_26				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
27	Dd_27				1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
29	Dd_29																	1	1	1	1	1	1
30	Dd_30																		1			1	1
31	Dd_31																			1	1	1	1
32	Dd_32																			1	1	1	1
33	Dd_33																					1	1
34	Dd_34																					1	1

[Step 4] Having considering Table F.8 (d), it was understood that the design decision (6), (10), (11) or (23) could not be affected by the other decisions. These design decisions were categorised as *Class* 4 (see Table F.9). As the rows and columns related to them were eliminated, the matrix shown in Table F.8 (e) was obtained.

[Step 5] Table F.8 (e) shows that the design decision (18) cannot be affected by the other decisions. This design decision was classified as *Class* 5. Having eliminated the row and column associated with it, Table F.8 (f) was obtained.

Table F.8 (e) Study of the reachability matrix (Step 5)

		14	15	16	17	18	19	20	22	24	25	26	27	29	30	31	32	33	34
14	Dd_14	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
15	Dd_15	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
16	Dd_16	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
17	Dd_17				1														
18	Dd_18	1	1	1	1	$\boxed{1}$	1	1	1	1	1	1	1	1	1	1	1	1	1
19	Dd_19	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
20	Dd_20	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
22	Dd_22	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
25	Dd_25	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
26	Dd_26	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
27	Dd_27	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
29	Dd_29													1	1	1	1	1	1
30	Dd_30														1			1	1
31	Dd_31															1	1	1	1
32	Dd_32															1	1	1	1
33	Dd_33																	1	1
34	Dd_34																	1	1

Table F.8 (f) Study of the reachability matrix (after Step 5)

		14	15	16	17	19	20	22	24	25	26	27	29	30	31	32	33	34
14	Dd_14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	Dd_15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	Dd_16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Dd_17				1													
19	Dd_19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	Dd_20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	Dd_22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25	Dd_25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	Dd_26	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	Dd_27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
29	Dd_29												1	1	1	1	1	1
30	Dd_30													1			1	1
31	Dd_31														1	1	1	1
32	Dd_32														1	1	1	1
33	Dd_33																1	1
34	Dd_34																1	1

Table F.8 (g) Study of the reachability matrix (Step 6)

		14	15	16	19	20	22	24	25	26	27	17	29	30	31	32	33	34
14	Dd_14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	Dd_15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	Dd_16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	Dd_19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	Dd_20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	Dd_22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25	Dd_25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	Dd_26	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	Dd_27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Dd_17											1						
29	Dd_29												1	1	1	1	1	1
30	Dd_30													1			1	1
31	Dd_31														1	1	1	1
32	Dd_32														1	1	1	1
33	Dd_33																1	1
34	Dd_34																1	1

[Step 6] In order that strongly connected sub-graphs can be identified without difficulty, Table F.8 (f) was modified, by interchanging some rows and columns, as shown in Table F.8 (g) which indicates that the design decision (14), (15), (16), (19), (20), (22), (24) to (27) are strongly connected, i.e. they may affect each other. It was also recognised that these design decisions were not affected by the other decisions associated with the matrix. These design decisions were classified as *Class* 6. Having eliminated the rows and columns associated to them, Table F.8 (h) was obtained.

Table F.8 (h) Study of the reachability matrix (Step 7)

		17	29	30	31	32	33	34
17	Dd_17	1						
29	Dd_29		1	1	1	1	1	1
30	Dd_30			1			1	1
31	Dd_31				1	1	1	1
32	Dd_32				1	1	1	1
33	Dd_33						1	1
34	Dd_34						1	1

[Step 7] In Table F.8 (h), it was found that the design decision (17) and (29) could be eliminated from the matrix, as they have no value of "1" except their diagonal elements. The design decision (17) and (29) were classified as *Class* 7. Furthermore, it was found that the design decision (17) could not affect any other decisions, because the row (17) has no value of "1" in its row except its diagonal elements. This means that the design decision (17) should be at the end of the design-making sequence. As a result Table F.8 (i) was obtained.

Table F.8 (i) and (j) Study of the reachability matrix

		30	31	32	33	34
30	Dd_30	1			1	1
31	Dd_31		1	1	1	1
32	Dd_32		1	1	1	1
33	Dd_33				1	1
34	Dd_34				1	1

(i) Step 8

		33	34
33	Dd_33	1	1
34	Dd_34	1	1

(j) Step 9

[Step 8] Table F.8 (i) shows that the design decision (31) and (32) are strongly connected, and also that (30) as well as these two, can be eliminated from the matrix, since they have a value of "1" only for their diagonal elements. These design decisions were classified as *Class* 8. Consequently, Table F.8 (j) was obtained.

[Step 9] Table F.8 (j) indicates that the design decision (33) and (34) are strongly connected. These were classified as *Class* 9. It can also be said that these design decisions should be at the end of the decision-making sequence. As a result of the examination, the *design decision variables* were classified into 8 Classes according to the order of the elimination. Table F.9 summarises the examination and shows these Classes of the *design decision variables.*

Table F.9 The classification of the *design decision variables*

Classes	***Design decision variables*** [{(*), (*)} indicates those strongly connected]
Class 1	(5), (12), (13), (28)
Class 2	(1), {(2), (3)}, (4), (21)
Class 3	(7), {(8), (9)}
Class 4	(6), (10), (11), (23)
Class 5	(18)
Class 6	{(14), (15), (16), (19), (20), (22), (24), (25), (26), (27)}
Class 7	(17), (29)
Class 8	(30), {(31), (32)}
Class 9	{(33), (34)}

F.3.2 Phase 2: Developing a structural model of the *design decision variables*

Since the design process is carried out in a step-by-step manner, it is assumed that the *design decision variables* can be organised in a hierarchical structure based upon the classification defined in Phase 1. This classification, however, implies only that the design decisions cannot be affected by those belonging to the lower classes, while they could affect those of the lower classes. But, the relationships between the *design decision variables* are still too complicated to develop an understandable structure, because a particular *design decision variable* could be related to those belonging to any Classes lower than itself. It was, therefore, felt that a reasonable skeleton of the hierarchical structure needs to be established, in order to develop a sequence for the design decision-making. Consequently, it was decided to introduce the following two rules:

(a) a set of *design decision variables* strongly connected are dealt with as a single entity (e.g. the design decision (8) and (9) are grouped and handled together); and

(b) the relationships to be considered are limited to those which relate a particular *design decision variable* to the other variables belonging to the following Class (the Class below); if the particular variables has no relationships with any of those within the following Class, consider the next lower Class, and so on. As described in the adjacency matrix M_{DdDd}, the design decision (5) of Class 1 is, for example, associated only with the design decisions (1), (2), (3) and (4) of Class 2, despite the fact that the decision (5) can affect (11), which belongs to *Class* 4. Considering the design decision (13) of Class 1, however, since it has no relationship with any of the design decisions within Class 2, 3 or 4, the relationships with the design decision (14) of Class 5, which is four classes down from Class 1, is to be considered.

Having re-examined the relationships between the design decisions according to the rules explained above, the classification shown in Table F.9 was modified, and, consequently, a new classification, called "*Design Steps*", was developed as shown in Table F.10. Here, the design decisions (12) and (21) have been classified in *Design Step* 3 and 4, respectively, so that they are situated immediately before those which it may first affect. For the same reason, the design decision (13) and (28) belong to *Design Step* 4. These *Design Steps* are considered to describe a rational sequence of decision-making steps of the building design process. As a result, the structural model of the *design decision variables* was illustrated, in accordance with these *Design Steps*, as shown in Figure F.12, in which a sequence of the design decision-making is well described. Sorting the design decisions in the order of the Steps, the adjacency matrix, i.e. M_{DdDd}, as well as the corresponding reachability matrix, can be made block-triangular, as shown in Table F.11 and F.12, respectively.

Table F.10 A sequence of the design decision-making

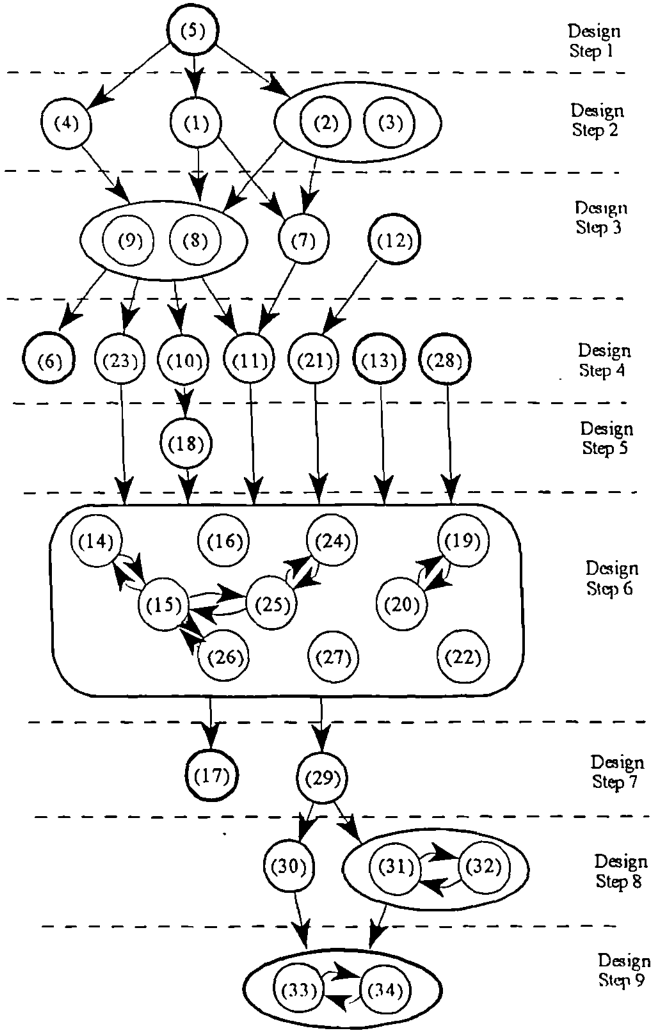
Design Steps	***Design decision variables*** [{(*), (*)} indicates those strongly connected]
Design Step 1	(5)
Design Step 2	(1), {(2), (3)}, (4)
Design Step 3	(7), {(8), (9)}, (12)
Design Step 4	(6), (10), (11), (23), (21), (13), (28)
Design Step 5	(18)
Design Step 6	{(14), (15), (16), (19), (20), (22), (24), (25), (26), (27)}
Design Step 7	(17), (29)
Design Step 8	(30), {(31), (32)}
Design Step 9	{(33), (34)}

Table F.11 The adjacency matrix which is made diagonal-triangular

		5	1	2	3	4	7	8	9	12	6	10	11	23	21	13	28	18	14	15	16	19	20	22	24	25	26	27	17	29	30	31	32	33	34
5	Dd_05		1	1		1							1								1				1	1	1		1						
1	Dd_01						1	1	1		1		1	1					1	1			1			1	1	1		1					
2	Dd_02				1		1	1	1		1		1					1	1			1			1		1	1							
3	Dd_03			1			1						1	1												1	1	1							
4	Dd_04							1												1	1				1		1		1						
7	Dd_07												1																						
8	Dd_08								1		1	1	1	1				1					1		1	1	1			1					
9	Dd_09							1				1						1										1							
12	Dd_12														1											1	1								
6	Dd_06																																		
10	Dd_10																	1																	
11	Dd_11																							1	1	1		1		1					
23	Dd_23																								1	1	1								
21	Dd_21																			1				1				1			1			1	
13	Dd_13																		1																
28	Dd_28																			1			1			1				1					
18	Dd_18																							1				1							
14	Dd_14																			1						1									
15	Dd_15																		1		1					1	1			1					
16	Dd_16																								1		1	1	1						
19	Dd_19																						1												
20	Dd_20																			1		1		1											
22	Dd_22																			1								1							
24	Dd_24																									1	1	1							
25	Dd_25																			1					1										
26	Dd_26																			1								1		1	1	1		1	
27	Dd_27																						1			1									
17	Dd_17																																		
29	Dd_29																														1	1		1	1
30	Dd_30																																		1
31	Dd_31																																1		1
32	Dd_32																															1			
33	Dd_33																																		1
34	Dd_34																																	1	

Table F.12 The reachability matrix which is made diagonal-triangular

		5	1	2	3	4	7	8	9	12	6	10	11	23	21	13	28	18	14	15	16	19	20	22	24	25	26	27	17	29	30	31	32	33	34
5	Dd_05	1	1	1	1	1	1	1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	Dd_01		1				1	1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	Dd_02			1	1		1	1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	Dd_03			1	1		1	1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	Dd_04					1		1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	Dd_07						1						1						1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	Dd_08							1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	Dd_09							1	1		1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	Dd_12									1					1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	Dd_06										1																								
10	Dd_10											1						1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Dd_11												1						1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	Dd_23													1					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	Dd_21														1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	Dd_13															1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
28	Dd_28																1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	Dd_18																	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	Dd_14																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	Dd_15																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	Dd_16																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	Dd_19																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	Dd_20																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	Dd_22																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	Dd_24																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25	Dd_25																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	Dd_26																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	Dd_27																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Dd_17																												1						
29	Dd_29																													1	1	1	1	1	1
30	Dd_30																														1			1	1
31	Dd_31																															1	1	1	1
32	Dd_32																															1	1	1	1
33	Dd_33																																	1	1
34	Dd_34																																	1	1



Design Step 1	(5)	Noise insulation priorities
Design Step 2	(1)	Daylight priorities
	(2)	Sunshine priorities
	(3)	View priorities
	(4)	Ventilation priorities
Design Step 3	(7)	Orientation of the building
	(8)	Form of the building
	(9)	Use of rooflights
	(12)	Construction type
Design Step 4	(6)	Position of the building on the site
	(10)	Roof shape
	(11)	Glazing orientation and related glazing area
	(23)	Primary function of side windows
	(21)	Number and position of rooflights
	(13)	Functional connections
	(28)	Reflectance of the interior
Design Step 5	(18)	Rooflight profiles
Design Step 6	(14)	Accommodation plan
	(15)	Room depth
	(16)	Use of natural ventilation
	(19)	Glazing materials for rooflights
	(20)	Glazed area for rooflights
	(22)	Area and dimension of individual rooflight
	(24)	Glazing material for side windows
	(25)	Glazed area for side windows
	(26)	Window shapes and positions
	(27)	Shading devices
Design Step 7	(17)	Need for mechanical ventilation or air-conditioning
	(29)	Function of artificial lighting
Design Step 8	(30)	Lighting system
	(31)	Lamp types
	(32)	Lighting luminaires
Design Step 9	(33)	Arrangement of the luminaires
	(34)	Lighting control system

Figure F.12

A sequence of the design decision-making regarding daylighting and lighting issues in particular

Appendix G

Appendix G

CHECKLIST FOR INTER-DISCIPLINARY BUILDING DESIGN WORKING WITH PARTICULAR REFERENCE TO DAYLIGHTING AND LIGHTING DESIGN ASPECTS

This checklist indicates "watch points" for inter-disciplinary building design working with particular reference to daylighting and lighting design aspects. It was developed on the basis of the framework explained in Chapter 4 of this thesis, using information extracted from publications. The information was itemised and shown in Appendix D. In this checklist, the watch points may be followed by the reference numbers representing relevant knowledge items. The published materials used, and corresponding reference numbers, are as follows:

(BS8207)	British Standard Institution, BS8207 "*Code of practice for Energy Efficiency in Buildings*", 1985
(BS8206_1)	British Standard Institution, BS8206 "*Lighting for Buildings, Part 1 Code of practice for artificial lighting*", 1985
(BS8206_2)	British Standard Institution, BS8206 "*Lighting for Buildings, Part 2 Code of practice for daylighting*", 1992
(AM)	The Chartered Institution of Building Services Engineers (CIBSE), "*Application Manual Window Design*", 1987
(CIBSE)	The CIBSE, "*Code for Interior Lighting*", 1984
(UB)	Reid, E., "*Understanding Buildings*", Longman Scientific & Technical, 1984
(BRE)	Building Research Establishment (1983), "Lighting controls and daylight use", BRE Digest 272
(Lecture_93)	Lecture note, "Harnessing Daylight" (Lecturer: Joe Lyne), Mid Career College, London, April 1993

The outline of this checklist is illustrated in Figure 4.18 in Section 4.4, Chapter 4 of this thesis.

G.1 *Briefing*

Design issue (1) General outline of the requirements

Consider the client's requirements in terms of:

(1) Aim of the project: Agree with your client on the aim of the project.

(2) Budget: Clarify the client's financial requirements.

(3) Timetable: Have you established a timetable for the project?

(4) Use of the building: Define the use of the building, including change of use to be allowed for.

(5) Accommodation: What accommodation is required?

(6) Activities carried out: Study what activities will be carried out within each space of the building.

(7) Visual tasks: Identify visual tasks carried out within each space of the building.

(8) Occupation pattern: Study the occupation pattern of each space within the building in relation to the activities; how many occupants are expected; how frequently do they enter and leave the space?

Design issue (2) Design objectives

Having studied the client's requirements, establish design objectives in terms of the design aspects, including:

(a) energy efficiency
(b) thermal comfort
(c) air quality
(d) visual environment (lighting)
(e) visual environment (view)
(f) acoustic consideration
(g) structural consideration
(h) external environment
(i) cost
(j) aesthetics

Design issue (3) **Context of the scheme**

(1) Boundaries / ambient environment: Examine the surrounding development of the site, including boundary fences and other enclosures, e.g. buildings surrounding the site.

(2) Daylight availability: Examine daylight availability of the site, considering any possible obstructions, e.g. buildings adjacent to the site, trees etc; Check the required level of natural light; enclosed and shaded site may require more use of artificial lighting.

(3) Sunshine duration: Examine sunlight duration on the site.

(4) View / out-door scene: Study the surrounding development in relation to the provision of view.

(5) Noise sources: Examine acoustic environment of the site, considering current or potential noise sources.

(6) Physical pollution: Examine the atmospheric environment of the site, in terms of the effects on daylighting and natural ventilation.

(7) Ambient climate: Study the ambient climate of the site, e.g. wind direction and rain fall?

(8) Local authorities and statutory regulations: Examine the constraints related to the local planning authority and statutory regulations?

Design issue (4) **Feasibility study**

Considering the building's functions, quality and the needs of the client and users, assess the feasibility of the project in terms of

(a) cost

(b) technical practicality

(c) social effects

(d) aesthetic expectations.

Study whether or not the client's requirements and the design objectives are viable in functional, technical and financial terms. If not, discuss them with the client with a view to adjusting the brief.

Design issue (5) Performance criteria / environmental standards

Establish the following performance criteria:

(1) Energy targets

(2) Thermal comfort level

(3) Air qualities

(4) Illuminance level: Determine the illuminance level required for each space considering the characteristics of the visual tasks and occupation pattern of the interior (CIBSE[1][2]).

(5) Uniformity of illuminance: Consider the uniformity of illuminance both over task area and between working area and non-working area (BS8206_1[7], BS8206_2[43][43']).

(6) Target average daylight factor: Establish target average daylighting factor, taking account of the occupation pattern in terms of probable hours of use of the building, the illuminance level to be satisfied, daylight availability of the site, and the accommodation (AM[58][59][60], BS8206_2[33]).

(7) Colour properties regarding artificial light sources: Considering the function of the room, the characteristics of the visual tasks and the impression the lighting is required to create, determine colour properties of artificial light sources, in terms of appropriate apparent colour (correlated colour temperature) and an appropriate colour rendering group (BS8206_1[10][11], BS8206_2[57]).

(8) Noise insulation level

(9) Cost range criteria

G.2 *Development of a design solution*

Design issue (6) Design approaches / priorities

[*Design Step* 1]

Dd_05 Noise insulation priorities

Is effective sound insulation essential? (AM[19])

Examine current and/or potential external ambient noise level; Consider the activities carried out in terms of limits of intruding noise; Consider also internally generated noise which needs to be constrained within the building.

[*Design Step* 2]

Dd_01 Daylight priorities

Consider the use of daylight for energy efficiency in the building (BS8207[4]); Determine whether daylight is essential, desirable, unimportant, or to be restricted or excluded (AM[8][9][10][11][12]).

Occupation pattern: Is the building occupied during daylight hours?

Daylight availability: Examine the ambient environment, including surrounding development (AM[20]).

Dd_02 Sunshine priorities

Determine whether sunshine is limited or excluded (AM[14][15], BS8206_2[20][22']); What time of the day and year does sunshine need to be limited? (AM[14]);

Consider broad decisions on sunlight admission taking account of:

Use of the building: Is the provision of sunlight required? Do the occupants in the interior have reasonable expectation of direct sunlight? (BS8206_2[24']);

Activities carried out: Do the activities carried out in the interior require the provision / exclusion of sunshine? (AM[15]);

Ambient environment: Surrounding buildings and topographical constraints will reduce the potential maximum. (AM[13]);
Sunlight duration: In many building discomfort and overheating may occur if the annual penetration of sunlight exceeds one third of probable sunlight hours (BS8206_2[26][28]);
Thermal comfort and energy consumption: Sunlight entering a room can have a significant effect on thermal comfort and the energy consumption of the building. (BS8206_2[25]);
Orientation: Consider the orientation for sunshine so that it is balanced against other requirements such as the provision of view (AM[13]).

Dd_03 View priorities

Determine whether the provision of view is essential, desirable or unnecessary/undesirable? (AM[16]);
View: A view out-of-doors should be provided irrespective of quality unless an activity requires the exclusion of daylight (BS8206_2[7]); Examine the nature of the external scene (BS8206_2[10]);
Orientation: Consider the compatibility with requirements for sunshine if the view requirements constrain orientation (AM[17]).

Dd_04 Ventilation priorities

Consider the use of natural ventilation wherever possible (BS8207[4]).
External noise level: Does noise insulation require fixed windows and mechanical ventilation? (AM[18',19]);
Atmospheric pollution: Sealed windows and mechanical ventilation or air conditioning may be required (AM[28][31]);
Ambient climate (wind): Does natural ventilation prove difficult to control satisfactory if the site is subjected to strong wind? (AM[28][32])

Design issue (7) Building's arrangement on the site

[*Design Step* 3]

Dd_07 Orientation of the building

Explore the massing and siting of the building taking account of daylighting (AM[9][11][35]);

Sunshine priorities: Take account of the admission of sunlight and overheating in summer (BS8206_2[23], AM[13], BS8207[6]).

View: If view requirements constrain the orientation, examine compatibility with requirements for sunshine (AM[17]);

Ambient climate (wind): Consider the effect of tall building on the wind environment in surrounding areas (AM[33]).

[*Design Step* 4]

Dd_06 Position of the building on the site

Explore the siting in relation to the proposed building form, considering the effect of overshadowing (AM[35][39], BS8206_2[23]).

Daylight priorities: If daylight is essential or desirable, find the position which offers minimal external obstruction (AM[20][37]);

Ambient environment: Study the site conditions in terms of the duration and extent of site shading in relation to the surrounding development (BS8206_2[72]); Consider rights to light, sunshine and privacy of the neighbours (AM[24,25,26]); Present an acceptable compromise between the requirements for sunlight of the new building and those of neighbouring buildings (BS8206_2[73]);

Noise insulation priorities: Do external noise sources constrain the positions of the building? (AM[20])

Design issue (8) Building form

[Design Step 3]

Dd_08 Form of the building

Explore the form of the building, in relation to its orientation and position, taking account of the ambient environment. (AM[35, (20,29)], BS8206_2[23])
Daylighting: Develop a building form taking account of daylight priorities and use of rooflights (UB[7][9], AM[9]); Have you considered the effect of plan depth on light penetration? (UB[8]); Consider the access to skylight in relation to the daylight availability (AM[37]);
Sunlight and overshadowing: Consider building height, plan shape, profile or orientation, so that the overshadowed area can be diminished or arranged to occur at times of least inconvenience (AM[39][40][41], BS8206_2[23]); Take care of the neighbours' rights to light and sunshine (BS8206_2[73], AM[23-25]);
Ventilation: In the case of natural ventilation, maximum recommended room depth is 6m for side-lit rooms in office buildings (AM[18], BS8207[4]);
Ambient climate (wind): The building height and depth may have to be reduced due to the effect of the ambient climate, wind in particular (AM[33]);
Energy consumption: Consider the implication with energy consumption in relation to lighting and ventilation methods (AM[29'], BS8206_2[75])
Statutory regulations: Have you consulted local planning authority and other statutory regulations? (AM[21,23])
Aesthetics: Have you considered aesthetics of the building? (BS8206_2[2])

Dd_09 Use of rooflights

Daylight priorities: If daylight is essential, consider the use of rooflights in order to increase daylighting (AM[9], UB[11]);
Atmospheric pollution: In heavily polluted areas, or where dirty process occur, rooflights will be inefficient unless cleaned frequently (AM[31"]);
Form of the building: Does the proposed building form allow for the use of rooflights? (AM[50], UB[9]);

Solar gain: Care must be taken to avoid undesirable solar gain because rooflights make a building particularly vulnerable to overheating by the high summer sun (BS8207[13], UB[11]).

Dd_12 Construction type

Select a construction type appropriate for the intended use in terms of the building's thermal behaviour (BS8207[7]).

[*Design Step* 4]

Dd_10 Roof shape

Building form: Consider roof shape as developing a form of the building, taking account of the use of rooflights (UB[7,9,11], AM[35,68]);
Ambient climate: The local climate, e.g. the likelihood heavy snowfall should be taken into account (AM[34]).

Dd_11 Glazing orientation and related glazing area

Explore glazing orientation and related glazing area, in relation to the proposed building form and its orientation, considering daylighting as well as thermal implications (UB[1]).
Daylighting: If daylight is essential or desirable, consider the daylight availability (AM[20][37]); If daylight is unimportant, glazing orientation and area are virtually unrestricted by daylighting consideration (AM[11]);
Sunshine and solar gain: Is there any preference for sunlight (sunshine and solar gain)? (BS8206_2[24]); Plan the orientation and disposition of rooms and their windows carefully so that the best control of sunlight penetration is achieved (BS8206_2[65]); Glazing should preferably be oriented due north when sunshine is to be permanently excluded (AM[15]); for south facing glazing the solar gain in summer could be excessive without shading, causing thermal discomfort and, in air-conditioned space, increases energy demand. (AM[43])
Heat loss: In heated spaces, north facing glazing should have the minimum area compatible with acceptable daylighting or view to minimise heat loss (AM[43]);

Statutory: Examine statutory regulation, e.g. fire precaution (AM[22]);
Others: Consider the compatibility with requirements for sunshine and view requirements (AM[17]); Noise insulation requirements may call for reduced glazing area (AM[28][29][30]).

Design issue (9) Internal layout

[*Design Step* 4]

Dd_13 Functional connections of internal spaces

Identify the functional connections of internal spaces by examining the activities carried out within the building.

[*Design Step* 5]

(No design task regarding "internal layout" design is associated with Design Step 5.)

[*Design Step* 6]

Dd_14 Accommodation plan

Functional connection: Consider the functional connection in terms of activities carried out, thermal comfort level (BS8207[3]);
Daylighting and room depth: If daylight is essential, consider shallow side-lit interior unless roof-lights are used (AM[9], UB[8]); Consider the possibility of multi-lateral fenestration for better daylight quality as well as natural ventilation (AM[103]);
Sunshine: Confirm that the requirements for access to, or exclusion of, sunlight can be achieved in the layout under consideration (AM[38]);
Visual environment: Adjacent rooms should not contrast harshly with each other in either brightness or the colour of the illuminance (BS8206_2[58], UB[35]);
Energy efficiency and thermal comfort level: Examine the possibilities of protecting main areas of accommodation by adjacent lobbies, passages and similar spaces not necessarily heated to the same standard, considering the activities carried out and their thermal comfort level (BS8207[3]).

Dd_15 Room depth

As the accommodation plan is developed, consider the effects of the room depth on:

Daylighting: Examine the room depth and daylight penetration in terms of no-sky line and limiting depth (AM[82]-[85],[88], BS8206_2[11], UB[8]);

Ventilation: In the case of natural ventilation, consider its implication with the room depth: maximum recommended room depth is 6m for side-lit rooms in office buildings (AM[18], BS8207[4]);

View: The most limited views occur in a deep room when windows are confined to one wall only (BS8206_2[13]).

Design issue (10) Main ventilation methods

[*Design Step* 6] and [*Design Step* 7]

Dd_16 Use of natural ventilation

Dd_17 Need for mechanical ventilation or air-conditioning

Consider the use natural ventilation wherever possible (BS8207[4], AM[18], UB[5]); Consider the requirements for fixed glazing in relation to: (a) noise insulation (AM[18][28]), (b) atmospheric pollution (AM[28]), and (c) wind (AM[32]); Excessive solar gain causes serious discomfort and, in air-conditioned buildings, unnecessary use of energy in cooling (BS8206_2[25]).

Design issue (11) Window design / fenestration

[*Design Step* 4]

Dd_28 Reflectance of the interior

Surface reflectances of the interior should be such that inter-reflected light in the space is strong and widespread (BS8206_2[33'][35']); To avoid glare from windows, window walls, the window reveals and the interior surfaces adjacent to rooflights should be of high reflectance (white or light-coloured) (BS8206_2[36]); Considering also the appearance of the interior.

A. *Rooflight*

[*Design Step* 4]

Dd_21 Number and position of rooflights

Consider the number and position of rooflights taking account of examine external obstructions (AM[20][36]).

Uniformity of illuminance: Assess the uniformity of daylight factor in relation to space/height ratio and the distance between any wall and the nearest rooflight (AM[75][76], BS8206_2[35]);

Structure: Is the distance between the rooflights feasible in terms of the structural span (AM[76])

[*Design Step* 5]

Dd_18 Rooflight profile

Select an appropriate rooflight profile considering: (a) roof shape, (b) solar gain in summer, (c) direction of light, and (d) provision of sunlight. (AM[51][52][53], Lecture_93); Take account of the effect of atmospheric pollution (AM[31]); Have you considered the heat loss in terms of the height of enclosed space relating the rooflight profile? (AM[66])

[*Design Step 6*]

Dd_19 Glazing materials for rooflight

Select appropriate glazing materials considering their (a) maintenance characteristics, (b) light transmittance, (c) thermal transmittance, (d) solar gain factor, (e) safety, and (d) colour effect (AM[54]).

Lighting and Glare: Consider light transmittance in relation to the glazed area and target average daylight factor (AM[61][88]); Diffusing or patterned glasses may cause glare (AM[113]);

Solar gain: Consider solar gain factor in relation to the control of the sunlight (AM[65][68], BS8206_2[21]); Consider low transmission solar glazing where large areas of glass are needed for view or appearance (AM[71], BS8206_2[68]);

Colour effect: Consider the effect on colour perception when tinted glazing is used (BS8206_2[39']);

Heat loss: Examine heat loss through the glazing area taking account of glazed area and the U-value of the glazing materials (AM[54][55][56][63]); Consider double glazing if possible (BS8206_2[77]).

Dd_20 Glazed area for rooflights

Lighting: Having considered daylight availability, estimate glazing area in relation to the target average daylight factor (AM[36][58][61], BS8206_2[79][82]); Consider the effects of the ambient environment and climate: (a) glazing area may need to be increased for daylighting in heavily polluted areas (consider correct factors for glazing) (AM[31']); (b) Consider the effect of shading devices (glazed areas may need to be increased) (BS8206_2[67]);

Heat loss and solar gain: Examine its thermal implication, i.e. heat loss (AM[55][56][63][64][65][66], BS8206_2[77]) and solar gain (AM[68], BS8206_2[77]), in relation to the glazing materials; Reduce glazing area in the site exposed to wind in relation to the building form (AM[32]);

Statutory requirements: Have you considered statutory requirements, e.g. fire precautions (AM[22]);

Finalizing the glazed area for rooflights: Reconcile thermal consideration with daylighting demands, if necessary, by manipulating the area or other physical parameters of the rooflighting (AM[73]).

Dd_22 Area and dimension of individual rooflights

Determine the area and dimension of individual rooflights, taking account of (a) the building form in terms of orientation of glazing and glazing types (BS8206_2[80]), (b) the activities carried out in terms of preferences for sunlight, and periods of occupation (BS8206_2[24]), and (c) external obstruction (AM[36]).
Uniformity of illuminance: Plan the rooflights so that poor distribution is avoided. (BS8206_2[29']); Is there any likelihood of glare? (BS8206_2[29"])
Solar gain: Plan the rooflights so that sunlight is controlled (AM[52], BS8206_2[65]).
Heat loss: Consider heat loss in relation to the orientation of the rooflights (BS8206_2[77][79][80]);

B. ***Side Windows***

[*Design Step* 4]

Dd_23 Primary function of side windows

Clarify the primary function of side windows: either (a) for view, (b) to enhance the overall appearance of interiors, or (c) for illumination of visual tasks (AM[46], BS8206_2[5][16]); Consider the daylight priority, daylight availability, and view priorities (AM[11][20], BS8206_2[5]).
Energy consumption: Consider the energy implication of the building, in relation to the form of the building, daylighting and ventilation methods, taking account of the ambient environment (AM[20][29']);
Aesthetics: Have you considered aesthetics of the building? (BS8206_2[2])

[*Design Step* 5]

(No design task regarding "side window" design is associated with Design Step 5.)

[*Design Step* 6]

Dd_24 Glazing materials for side windows

Select glazing materials in relation to glazed area in terms of: (a) luminous transmittance, (b) solar gain factor, (c) colour effect, (d) thermal transmittance, and (e) acoustic attenuation (AM[81][88], BS8206_2[80]); Take account of orientation of glazing (BS8206_2[80]) and the primary function of windows (AM[81]).

Lighting and glare: Consider light transmittance in relation to the glazed area and target average daylight factor (AM[88]); Patterned glass may become a glare source (AM[113], BS8206_2[47]);

Solar gain: Consider solar gain and solar protection in terms of the control of sunlight (AM[65][68][71][112], BS8206_2[68]); Consider low transmission "solar" glazing where large areas of glass are needed for view or appearance (AM[71], BS8206_2[68]); Low-transmittance glazing reduces sky glare but is unlikely to attenuate the sunlight sufficiently to eliminate glare;

Colour properties: Consider the affect on colour perception when tinted glazing is used (AM[81], BS8206_2[39']);

Heat loss: Examine heat loss through the glazing area taking account of (a) glazed area (AM[86]) and (b) the U-value of the glazing materials (AM[63,86,91], BS8206_2[77]); Consider use of double glazing if possible (BS8206_2[77]);

Privacy: Consider the desire for privacy which may imply the permanent use of curtains or non-transparent glazing. (AM[81]);

Noise: External noise penetration may be reduced by following expediences: (a) use of fixed windows, (b) use of acoustic double windows, (c) use of thick glass, and (d) reduction of window area (AM[99]); External noise level may demand fixed glazing (AM[18']);

Ventilation: Consider the implications for ventilation if a fixed window is considered (AM[19]); Consider also the ambient climate in terms of the advisability of using fixed glazing if the site is subjected to strong winds or where the proposed building will be much taller than its surroundings (AM[32]);

Aesthetics: Have you considered the external appearance? (BS8206_2[2])

Dd_25 Glazing area for side windows

Consider the primary function of windows: whether they are for daylight or for view (BS8206_2[14][15]).

Daylighting: Consider the glazed area for daylighting based upon: (a) target average daylight factor, (b) daylight availability in terms of the angle subtended by the sky visible from the centre of the window, (c) luminous transmittance of glazing material, (d) size and shape of interior, and (e) reflectance of interior surface (AM[20][66][88]); Examine the room depth (size and shape) in relation to daylighting in terms of no-sky line and the depth limit (AM[82][83][84]);

View: Consider the provision of view taking account of the (a) the type of view, and (b) the size of the internal space (AM[104], BS8206_2[11][14][15]).

Statutory: Check statutory regulations, such as fire precautions (AM[22]).

Heat loss: Examine heat loss through the glazed area in relation to glazing materials (U-value) and orientation, taking account to ambient climate (wind) (AM[20][32][91], BS8206_2[77][80]).

Solar gain: Assess summer solar gain taking account of the orientation of the windows, outdoor obstructions, glazing materials and choice of solar protection (AM[92][93], BS8206_2[67]).

Noise: External noise penetration may be reduced by reducing window area (AM[99]).

Others: Consider physical pollution in terms of glazing maintenance (AM[28][30]).

Finalizing glazed area for side windows: Having assessed average daylight factor, heat loss, solar gain, view and noise level in relation to glazing materials, reconcile thermal consideration and acoustic consideration with daylighting requirements, if necessary, by manipulating the area or other physical parameters of the rooflighting (AM[100], BS8206_2[79][82]); If total glazing area cannot be made large enough for adequate general daylight, supplementary artificial lighting is needed to enhance the general room brightness in addition to any need for task illumination (BS8206_2[19]).

Dd_26 **Window shape and position**

Optimise the window shape (BS8206_2[11'][11"]) and position (BS8206_2[12][24]); Consider multilateral fenestration wherever possible (AM[103]).

Daylighting: For interior lighting, consider: (a) activities carried out (work stations), (b) occupation pattern, (c) outdoor obstruction, and (d) room depth in terms of daylight availability (AM[20][36][82][83][84][85][105]); Examine (a) uniformity (BS[33'], BS8206_2[11']), (b) modelling (BS8206_2[41]), and (c) glare (AM[107][111][112], BS8206_2[37][38][65]);

View and privacy: Consider the window position in relation to the provision of view taking account of the position and mobility of occupants (AM[115][116][118],BS8206_2[8][11][11'][11"][12],UB[3][4]); Consider also the requirement of privacy (AM[117], UB[4]);

Solar gain: Assess solar gain in relation to position and glazing materials (AM[15][93], BS8206_2[24][65]);

Heat loss: Consider the position (orientation) of the windows, taking account of the form of the building (AM[20][33][92]);

Ventilation: Consider multilateral fenestration to enhance natural ventilation (AM[18'][103], UB[5]);

Structure: Consider window shape and position in terms of structural strength (UB[6]).

Aesthetics: Have you considered the external appearance? (BS8206_2[2])

Dd_27 Shading devices

(This is common to both "*Rooflight*" and "*Side windows*")

Select appropriate shading devices in terms of the control of solar gain and glare (BS8206_2[65]-[71], CIBSE[1]), taking account of:

(a) glazing materials (AM[68]),

(b) glazing orientation (AM[96][97], BS8206_2[65]),

(c) rooflight profile (BS8206_2[66], CIBSE[2]),

(d) window shape (AM[96][97], BS8206_2[69][69'][70]),

(e) glazing area in relation to average daylight factor (BS8206_2[67]), and

(f) energy consumption (BS8207[1], BS8206_2[68]).

Consider also their effects on: (a) heat loss (UB[36]), (b) natural ventilation (BS8206_2[71]), (c) provision of view (BS8206_2[71]), and (d) external appearance (aesthetics) (BS8206_2[2]).

Design issue (12) Artificial lighting installation

[Design Step 7]

Dd_29 Function of artificial lighting

Specify the function of the artificial lighting in relation to daylight performance, considering

(a) daylight priorities (AM[9]-[11], BS8206_1[3])
(b) required illuminance level (BS8206_2[55])
(c) average daylight factor and room depth (AM[121]-[125], BS8206_2[30]-[32])
(d) uniformity of illuminance (BS8206_2[34][54]).

Consider the integration of daylight and artificial light. (BS8206_2[50]-[64]) in terms of:

(a) illuminance (BS8206_2[56],[61])
(b) balance of daylight and artificial light (BS8206_2[51][52])
(c) modelling (BS8206_2[53],[62])
(d) contrast between interior and exterior (BS8206_2[54][55])
(e) colour appearance (BS8206_2[57],[63][64])
(f) sequence of spaces (BS8206_2[58][59]).

Consider also thermal and energy implications of artificial lighting (UB[13][14][43]).

[Design Step 8]

Dd_30 Lighting system

Select appropriate lighting system, i.e. general, localized or local lighting (CIBSE[6]).

Flexibility:

Do the activities and visual tasks carried out require the flexibility of location; Is correct information about the task location available?

Energy consumption:

Consider its effect on installation cost as well as energy cost; What is the function of artificial lighting: supplementary / permanent / task lighting? (AM[124])

Dd_31 Lamp type

Select appropriate lamp types considering the following characteristics:

(a) colour properties: consider appropriate apparent colour and colour rendering properties in relation to the activities and visual tasks carried out. (CIBSE[3][6]); When artificial lighting is used with daylight, consider the integration with daylight (UB[37], BS8206_1[3]);

(b) run-up time (CIBSE[4])

(c) lumen maintenance characteristics in relation to luminaires (CIBSE[4])

(d) stroboscopic effect (CIBSE[4])

(e) maintenance and life (CIBSE[4]).

Dd_32 Lighting luminaires

Considered safety in relation to the environmental conditions encountered (CIBSE[5], BS8206_1[20]).

Select appropriate lighting luminaires, in conjunction with the lamp type (CIBSE[3]), in terms of

(a) light distribution and the way of controlling glare

(b) utilization factor (BS8206_1[21], UB[46])

(c) luminaire reliability (CIBSE[5], BS8206_1[20]);

Assess the energy (thermal) implication of lighting (BS8206_1[19],UB[46]); Consider the heat gain from the lighting installation in relation to the necessity of ventilation (UB[21]).

[*Design Step 9*]

Dd_33 Arrangement of the luminaires

Arrange the luminaires considering the activities and visual tasks carried out, in terms of the position and mobility of occupants (BS8206_2[11]);

Assess:

(a) illuminance (UB[21][26])

(b) uniformity of illuminance (UB[38][40][41])

(c) appearance / modelling (BS8206_2[62])

(d) glare and specular reflection (UB[29])

(e) maintenance access (UB[22])

Control should permit individual luminaires or rows of luminaires parallel to window walls to be controlled separately (BS[29]); Zone luminaires carefully taking account of rooflights and windows (AM[125],BS8206_1[3])

Dd_34 Lighting control system

Select an appropriate lighting control strategy considering:

(a) daylight availability (AM[122,123,124], BRE);

(b) occupancy pattern: Have you examined the activities and visual tasks carried out, and the position and mobility of occupants; Have you considered occupation pattern? (BS8206_2[11], BRE)

(c) lamp type and luminaires (AM[126]-[131], BS8206_1[28]-[34])

Consider energy consumption and costs, both installation and running costs (AM[132], BS8206_1[13]-[23]).