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Intelligent Building Envelopes

Architectural Concept & Applications for Daylighting Quality

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Abstract

During the past few decades, buildings have been imposed to steadily extend their functionality at diminishing cost. Increasingly varying and complex demands related to user comfort, energy and cost efficiency have lead to an extensive use of mechanical systems to create a satisfactory indoor climate. The expanding application of control technology in this context has lead to the emergence of the terms *intelligent building* and *intelligent building envelope* to describe a built form that can meet such demands, be it to a varying degree of success. A multitude of definitions of intelligent building envelopes, however, opens for divergent interpretations of the design, operation and objectives of this type of envelope.

Within the scope of this research, intelligent behaviour for a building envelope is, similar to human intelligent behaviour, defined as *adaptiveness* to the environment by means of psychical processes of *perception*, *reasoning* and *action*, which enables the envelope to solve conflicts and deal with new situations that occur in its interaction with the environment.

This definition is used as a basis for an analysis of the functions an intelligent building envelope can be expected to perform in the context of daylighting quality, or an optimisation of the indoor luminous environment to the requirements of the individual building occupant. Among the characteristics discussed in this thesis, are the envelope's ability to learn the occupant's needs and preferences, to choose the most appropriate response in each situation, to make long-term strategies, to anticipate the development of environmental conditions, and to evaluate its own performance.

In addition, a number of physical applications, ranging from materials and components to building envelopes, are selected from research papers and architectural magazines and discussed for their ability to support the envelope's performance with regard to daylighting quality. Several trends are discussed: the increasing self-sufficiency of the building envelope; the co-operation between artificial intelligence and the material, form and composition of envelope elements; user-centered design and communication between occupant and envelope; and the increasing co-operation between architects, engineers and manufacturers to provide multi-layered and multifunctional envelope solutions, adapted to the climate, site and building function.

The use of adaptive solutions and an extended functionality and flexibility of the building envelope, however, in no manner reduces the need for meticulous design according to local climate and site, building program, and the quality of the indoor environment. All of the sources consulted during the course of this Ph.D. stress time and time again how *difficult* it is to control the operation of the envelope components according to the local environment, and, simultaneously, how *important* it is to do so.

Acknowledgements

Up to one year ago, I was determined to keep a safe distance from the worn-out cliché of the Ph.D. candidate working around the clock, oblivous to any reality outside of dissertation, with a facial colour that blends into the background wallpaper. (http://www.phdcomics.com features comic strips on this topic - hilarious!) As the deadline approached, however, the working day was stretched and intensified progressively in order to incorporate ever more data, and to find the vocabulary and syntax that would convey my thoughts meticulously. If completing a Ph.D. project is a tough nut to crack for any researcher, it is a mere work of Sisyphus for a perfectionist.

When finally this book now has become a reality, it is due to the patience, support and guidance of a number of people, to whom I express my sincere gratitude.

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A final thanks to Berit Østberg, whose *risp* expresses so perfectly one of the most valuable lessons learnt during these past few years of work, and who generously allowed me to reprint the *risp* as an inspiration to all readers [Østberg 2003:92].

"The things you think about during cycling wouldn't have sprung to mind in front of the computer screen."

Annemie

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1 Introduction

1.1 Background

Intelligent building envelopes are controversial. Rumours of their excessive and unmitigated control of the indoor environment driving the building occupants crazy, circulate with increasing frequency. Despite their endeavour towards a green image, their high-tech, so-called intelligent, components are suspected to use more energy than they save in operation. Their moveable parts, though they cost an arm and a leg, are prone to break down and need ample care by higly-trained personnel.

Why would anyone opt for this type of building envelope?

The generator for this Ph.D. research has been to confront such mental images of intelligent building envelopes - not with the intention to display all of its flaws, but, on the contrary, to evaluate whether and how this type of envelope can be designed and implemented to make a positive contribution to a building's indoor environment.

1.1.1 The emergence of intelligent building envelopes

During the past few decades, buildings have been imposed to steadily extend their functionality at diminishing cost. Increasingly varying and complex demands related to user comfort, energy, and cost efficiency have lead to an extensive use of mechanical systems to create a satisfactory indoor climate. The expanding application of control technology in this context has lead to the emergence of the terms *intelligent building* and *intelligent building envelope* to describe a built form that can meet such demands, be it to a varying degree of success.

In an architectural context, the term *intelligent building envelope* has become a common denominator for a type of built form that uses artificial intelligence to provide the indoor environment with dynamic heating, cooling, lighting and ventilation, aiming to procure an optimal balance between occupant comfort and energy efficiency.

A multitude of definitions of intelligent building envelopes, however, opens for rather divergent interpretations as to the manner in which this balance between occupant comfort and energy use is to be achieved. On the one hand, intelligent building envelopes are commonly associated with a high-tech image, featuring a range of innovative technologies that dominate the visual expression of the building. On the other hand, intelligence is often related to vernacular architecture, or to architecture that is designed, used and maintained in an intelligent manner.

(left) [Schittich (ed.) 2001:164] © Thomas Ott (right) [Schittich (ed.) 2001:11] © Klaus Zwerger

Figure 1-1: *Diverging depictions of intelligent building envelopes: (left) curved aluminium sunscreen and light-deflecting elements give a high-tech visual expression to an administration building in Wiesbaden, designed by Herzog + Partner; (right) a traditional Japanese house, where bamboo shades and paperfaced, light-permeable sliding doors with timber frames make the envelope adaptable to a wide range of environmental conditions.*

Building envelopes function as an environmental filter. They form a *skin* around the framed structure of the building and manipulate the influence of the outdoor on the indoor environment, but are not necessarily part of the load-bearing structure itself [Glass 2002].

What then distinguishes an *intelligent* building envelope from a conventional one? The term *intelligent* currently being a buzzword, involves the danger of ending up with a meaningless quality label when applied to the building envelope. What are the qualities one projects onto a building envelope by calling it *intelligent*? Does the adjective mainly refer to the intelligent design and maintenance of the building envelope by humans, or can also an envelope's behaviour *in se* be qualified as intelligent? What differentiates an intelligent building envelope from a conventional one?

When inspecting an inanimate object for intelligent behaviour, one needs to realise that *intelligence* in this context merely is a projection. A building envelope is not intelligent in the same manner a human or animal is. Building envelopes do not require the same intelligence, they do not need to perform the same manner a human does. What they *are* expected to do, however, is to optimise their performance as an environmental filter. And to this purpose, they can be designed with certain characteristics that mimick human intelligence, to support and enhance the outcome of detail and care in the use of material, form and composition.

Intelligence in building envelopes can take on different meanings, depicting characteristics and qualities that fit the personal and professional interest, goals, and beliefs of a particular author or organisation. This explains the emerging divergence in definitions on the concept of intelligent building envelopes.

Within the scope of this research, *adaptiveness* was chosen to be the main characteristic of intelligent building envelopes. Similar to the development of intelligence in human beings, *adaptiveness* of the envelope to its environment, by means of psychical processes of *perception*, *reasoning* and *action*, allows for interaction with the environment, and enables the envelope to solve conflicts and deal with new situations that occur in this environment.

1.1.2 Applying envelope intelligence to promote daylighting quality

Proper daylighting strategies always start with architectural design adapted to local climate and site, and to the specific function of the building; this can be modelled in the design phase and then incorporated in the form and material use of the building. In a real-time environment, however, daylighting poses a range of variable and sometimes conflictive requirements related to occupant comfort and energy use, the nature and extent of which are difficult to predict and model on beforehand.

It is the intent of this thesis to evaluate whether and how an intelligent building envelope, as defined above, can be used as a tool to manage the challenges that arise in daylighting non-domestic buildings with regard to three areas of focus:

- Variability
- Conflicts
- Occupant behaviour

Daylight is a highly variable light source in intensity, spectral distribution and directionality. User studies, for example by Cooper & Crisp [1984], show that daylight's variability is a quality that in general is highly desired by building occupants; hence, it should not be filtered out by the building envelope, nor overcompensated for by artificial lighting. Simultaneously, however, daylight's variable intensity is found to be an important hinder to designers' deliberate application of daylight as a light source in buildings.

A second challenge for the use of daylight in non-domestic buildings is formed by variable and potentially conflictive demands of transparency versus privacy, of openness versus insulation, of access to daylight versus solar shading. In addition, due to the greenhouse effect, all daylight allowed indoors generates heat. As this heat gain only partially can be avoided by means of solar shading and blocking of near-infrared radiation, an advisable strategy would be to avoid the admission of superfluous daylight indoors and correspondingly to use the available daylight sources in the most effective manner possible [Smith 2004].

Coping with human behaviour forms a third type of challenge for successful daylighting strategies in non-domestic buildings. While lighting standards ensure the fulfilment of minimum requirements regarding visual comfort and visual performance, building occupants' physiological reaction to indoor daylighting conditions may vary according to individual, cultural and functional needs [Begemann *et al.* 1997; Hygge & Löfberg 1997] . In addition, human cost has grown to be at least as important as energy cost during the past few years; a decrease of 1% in occupant productivity is likely to spoil all expected energy savings [Fontoynont *et al.* 2002; IEA 2001]. The building occupants' acceptance of daylighting strategies is thus of the utmost importance.

1.2 Research questions

This background information generated the following research question:

> How does an intelligent building envelope manage the variable and sometimes conflictive occupant requirements that arise in a daylit indoor environment?

As this question touches several fields of application, it is untangled into more manageable steps:

> a) What characterises intelligent behaviour for a building envelope?
> b) How can these characteristics fruitfully be applied to promote daylighting quality?

The first question concerns the particular qualities that distinguish an *intelligent* building envelope. All building envelopes have the function of an environmental filter. What makes an intelligent building envelope stand out in its interaction with the environment?

The second question is related to the particular kind of service that can be expected from an intelligent building envelope with regard to daylighting quality. Daylighting non-domestic buildings serves a number of rather diverging goals, such as reducing the building's energy performance, improving aesthetics, optimising the occupants' visual performance, and providing a healthy, pleasant and productive work environment. Creating a desirable daylit environment indoors, however, requires more than merely opening up the facade and flooding the indoor environment with daylight. The appropriate admission and distribution of daylight in non-domestic buildings requires a thorough understanding of human response to spatial and temporal variations in lighting in the particular climate, site and indoor environment the building occupant is confronted with.

The manner in which the building envelope is able to handle the collection, admission and distribution of daylight indoors determines its successfulness in creating an appealing indoor luminous environment with an effective use of daylight sources. Which functions does the building envelope need to perform, and how does its *intelligence* influence the performance of those functions? When are these particular characteristics fruitful for daylighting quality?

1.3 Scope

1.3.1 The architectural concept of intelligent building envelopes

Intelligent building envelopes may be defined on the basis of a wide range of criteria such as the materials and components they consist of, the control algorithms they apply, and the goals they are designed to achieve. Within the scope of this thesis, it is chosen to focus on the envelope's characteristic behaviour, more specifically how the envelope adapts to the variations in its environment that occur over time.

The design and operation of intelligent building envelopes touches on a variety of fields of research, among which are engineering, architecture, psychology, chemistry, and computational and material sciences. The information these fields provide on the topic of intelligent building envelopes is, in this thesis, taken into account to the degree it is considered useful for the architectural design of an intelligent building envelope. Such an approach inevitably means for the extensive detail that exists in each of those fields to be reduced in the extractions used in this thesis; therefore, references are made to expert literature in the corresponding fields whenever appropriate.

The concept of *intelligent buildings* is not included in this thesis, as it comprises a much wider range of functions than does the building envelope, such as the communication network within the building. The performance of an intelligent building envelope as an environmental filter, however, does extend beyond the physical boundaries of the envelope itself. The envelope is for example likely to be connected to the same Building Energy Management System that is guiding mechanical ventilation, cooling, heating and lighting. Building plan and section, as well as indoor material use, will significantly influence the envelope's range of operation, particularly with regard to daylighting. In this thesis, nevertheless, focus is attempted restricted to the functionality of the building envelope; additional features are discussed only in their support and enhancement of the envelope's performance.

1.3.2 Building occupant

In an age of stunning technological development, it is tempting to regard the application of technology in architecture not as a means, but as the end in itself, superior to user concerns. However, the building envelope's function as an environmental filter does not only influence the building's energy use, but also the building occupant's health, comfort and well-being. The optimal building envelope needs to be able to handle requirements for transparency and privacy, insulation, ventilation and solar heat gain, daylight and solar shading, that vary with the occupants' individual, cultural and functional needs.

The main generator for choosing to place focus on the building occupant, is a genuine curiosity for the manner in which an intelligent building envelope can be defined by its impact on the people who are using the space on a daily basis, rather than being developed in terms of the technology available, or the conservation of energy.

While the building envelope's function as an environmental filter exerts a considerable influence on the building occupants' health, comfort and well-being, it is also frequently warranted in research literature that the acceptance of environmental control by the user is of the utmost importance. Section 1.1 already mentioned that human cost has grown to be more important than energy cost in operation of a non-domestic building, thus making occupant satisfaction and productivity an important financial issue. According to Fitzgerald & Fitzgerald, dissatisfied occupants may even actively counteract the controls: *"the most probable cause of a system's failure is people. By this we mean the non-acceptance of the system and, therefore, the philosophy and method of going around or "beating" the system"* [1987:248].

Other user groups, such as building owners, the maintenance staff and the design team are not included in the scope of this thesis.

1.3.3 Daylighting quality

The building envelope as an environmental filter manipulates the admission and distribution of daylight indoors, and thus the manner in which the occupant perceives the indoor luminous environment. Relevant issues in this respect are not only the particular light levels that are to be achieved indoors, but also the distribution of light, colour, directionality, view, privacy, and a feeling of control. All of these factors will be taken into account in this thesis. The scope of this research includes only visible, natural light. Shorter wavelengths (UV) and longer wavelengths (IR) are not considered in the analysis. Neither is artificial lighting, except for some examples in Chapter 5 where its design and operation are particularly integrated with natural lighting strategies.

The use of daylight in office buildings carries consequences in a wide variety of fields, such as energy use, finances, aesthetics, and ecology. These are discussed briefly in Chapter 3, however, the main point of focus is the manner in which daylight influences the indoor luminous environment on a daily basis, i.e., daylighting quality. While energy efficiency does not form the main point of focus in this thesis, the question as to how the available daylight sources can be taken into use effectively, is. If one can manage daylighting quality successfully with less incoming daylight, there are opportunities for energy saving. Daylight is a light source with high luminous efficacy and therefore offers the potential of energy savings when used instead of artificial lighting; the extent to which these savings can be achieved, however, depends on *"the efficiency of use of the available lumens"* [Smith 2004:396].

1.3.4 Office buildings

A system able to solve all problems for all building contexts does not exist; different strategies are needed for different operating environments. For each type of building, one needs to define the level of service that is required in daylighting according to the building program and the activities of the users. While the main focus of this Ph.D. lies on office buildings, it could be extended to other non-domestic buildings mainly used during daytime hours, such as schools, health care facilities and retail facilities, though the latter tend to exclude daylight to a large extent.

1.4 Rationale

An overall objective for this research has been to confront some of the mental images that circulate on the topic of intelligent building envelopes, and to explore alternative directions. Two issues in particular are discussed:

- Can an intelligent building envelope be reduced to the automation of components and functions?
- Can an intelligent building envelope be reduced to its visual expression or *toyerism*?

1.4.1 More than automation?

Does the architect decide upon the visual expression of the envelope, for the engineer afterwards to design its operation and automation? The concept of intelligent building envelopes often appears to be reduced to the use of artificial intelligence and the automation of functions and components. It is the aim of this thesis to explore the functionality and corresponding design of intelligent building envelopes, and to analyse alternatives in material use, form and composition of the building envelope for the design of daylighting functions. What kind of service can an intelligent building envelope be expected to provide? And how is this influenced by envelope morphology?

1.4.2 More than *toyerism*?

In some architectural projects, the use of high-tech elements in the building envelope has become a goal *in se* - a practice also called *"toyerism"* [Kroner 1997: 381] - aiming to achieve a high-tech visual expression in architecture rather than deploying the components for their specific functionality.

1.4.3 More than energy conservation?

In addition, the performance of an intelligent building envelope is often reduced to quantifiable measures such as energy, cost and recommendations included in the building code, related to a minimim value rather than best practice. Is it possible to shift focus to the individual user? Can an intelligent building envelope interact with and optimise its performance for a real user rather than basing its operation on standard recommendations?

1.5 Method

What is an intelligent building envelope? What does it do? Which tasks related to daylighting quality need to be fulfilled by the building envelope? And which devices can be deployed to perform exactly that task? In order to answer these questions, the intelligent building envelope is approached as a system, or *"a set of interrelated and interacting component parts that, when put together, function to achieve a predetermined goal or objective"* [Fitzgerald & Fitzgerald 1987:10].

After having developed an operational definition for an intelligent building envelope, the functions this envelope may be expected to perform in order to improve indoor daylighting quality are analysed, and the consequences of choosing particular physical applications to perform those functions are evaluated. Each of those steps is discussed in its own chapter, according to the structure depicted in Figure 1-2.

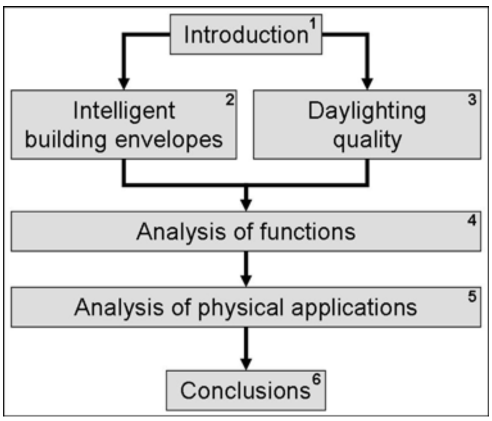


Figure 1-2: *The structure of the research strategy applied in this thesis.*

Gaining insight into the nature and operation of an intelligent building envelope, however, is neither evident nor straightforward. Focus on the individual components makes the interaction and organisation between them disappear. By focusing on the goals, there is no direct link to the manner in which those goals are expected to be achieved. By focusing on performance criteria such as energy and cost efficiency, there is a danger of having the actual building user fade into the background.

1.5.1 An operational definition for intelligent building envelopes

In order to avoid such pitfalls, it is decided to focus on an operational definition for an intelligent building envelope, or a process-oriented description of the envelope's behaviour; not what it *is*, but what it *does* [Sinding-Larsen 1994].

A first step towards this definition consists of a literature review within the field of building design, aiming to identify definitions and terminology related to an intelligent building envelope, and to abstract relevant characteristics for its behaviour. The resulting information, however, is not satisfactory, as the use of the term *intelligent* is found to have a myriad of applications, related to the use of high-tech components and artificial intelligence or to more diffuse concepts of rationality, sensibility and good judgement often associated with human intelligence.

Thus, another path is chosen: an exploration of intelligence in building envelopes based on the development of *intelligence in humans*. Can intelligence be ascribed a meaning that surpasses people's spontaneous association of *intelligence* to rationality or IQ? And can this be used to describe the behaviour that may be expected of an *intelligent building envelope*? This approach is evidently inspired by a rich tradition of organicism and antropocentrism, comparing the functionality of the building envelope, and architecture in general, to heliotropic plants, human skin, and similar elements (see Chapter 2 for a more detailed description). However, within the scope of this thesis, the approach does enable the development of an operational definition of *intelligent* building envelopes, related to concrete psychical processes.

Expert literature on the psychology of intelligence is explored, and relevant elements of intelligent behaviour are extracted. The main characteristic is the *adaptiveness* of the subject to its environment, by means of psychical processes of *perception*, *reasoning* and *action*, allowing the subject to deal with new situations and to solve problems that may occur when interacting with the environment. This information is used to elaborate an operational definition for intelligent building envelopes, the relevance of which is then assessed in comparison with existing definitions.

With this operational definition, it can be analysed how an intelligent building envelope can be used as a tool to achieve a diversity of goals, such as financial efficiency, optimal user comfort, and energy conservation. Within the scope of this thesis, focus is primarily aimed towards user requirements in daylighting: to analyse how an intelligent building envelope can collect, admit and distribute daylight indoors in order to create a satisfactory indoor luminous environment.

1.5.2 Characteristics of daylighting quality

On the subject of daylighting quality, plenty of literature sources are available. There appears to be a general agreement on the importance of daylighting and on the identification of factors relevant for its quality. Less consonance is discerned, however, on the significance of each of these factors, and on the extent of their interaction. Six conditions related to the indoor luminous environment are abstracted from literature:

- Luminous distribution
- Glare and veiling reflections
- Colour
- Directional properties
- Visual contact with the outdoor environment
- Individual control

The abstracted characteristics are applied in the analysis of an intelligent building envelope as an instrument to promote daylighting quality in non-domestic buildings. A systems approach will be used to analyse the nature and extent of interaction between the listed characteristics, and the consequences this interaction carries for the building occupant.

1.5.3 Functional analysis: envelope intelligence for daylighting quality

In linking objectives for daylighting quality to the operation of an intelligent building envelope, it may be tempting to automatically think in categories of existing daylighting devices and control systems. Several authors, among them Fitzgerald & Fitzgerald [1987] and Hoff [2002], warrant that, in a systems approach, one should try to separate tasks and devices as long as possible, in order to reduce the danger of automatically assigning a device to an objective while there might be alternative and more fruitful ways to assign tasks.

As explained earlier, for example, the functions a building envelope needs to be perform as an environmental filter are variable and sometimes conflictive. Therefore, one needs to distinguish between conflicts that appear within this functionality, or those that appear because of the physical components and materials that are chosen to execute those functions. Thus, there is a strict distinction in the thesis between a functional analysis of the envelope's tasks related to daylighting quality, and an analysis of the physical elements that may be deployed to perform those tasks.

In order to analyse the functions an intelligent building envelope can be expected to perform in the context of daylighting quality, a matrix is developed that interrelates each of the three characteristics intrinsic to envelope behaviour - *perception*, *reasoning* and *action* - with each of the six conditions related to the luminous environment identified by the literature review to contribute to daylighting quality (Figure 1-3).

	Perception	Reasoning	Action
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

Figure 1-3: *A matrix of interrelations between intelligent envelope behaviour and conditions in the luminous environment that are found to contribute to daylighting quality.*

Each of the matrix fields is analysed in a systemic pattern, and conflicts and opportunities are identified. Interaction between the different matrix fields, on the other hand, is not taken into account at this stage; this type of interaction is made concrete in the next stage of the systems analysis, where the choice of a particular device to perform the envelope function, creates boundaries for the indoor luminous environment that can be achieved.

1.5.4 Physical application: envelope intelligence for daylighting quality

After having analysed each of the matrix fields, a selection of physical applications is discussed for their potential to support the kind of functionality that is expected from an intelligent building envelope in the context of daylighting quality. These physical applications are identified in literature sources, with additional information provided by contact with the architects and manufacturers.

Consequence patterns generated by the use of each particular application are identified and evaluated for the nature and extent of functionality provided, and for the manner in which conflictive requirements are handled. Physical applications with a similar functionality are organised in groups, and their differences discussed. Strengths and weaknesses are assessed, and suggestions for increased adaptiveness are made.

1.5.5 The use of literature sources as a basis for the systems approach

In the search for an answer to the research questions, various kinds of data can be gathered, using techniques such as literature reviews, measurements, simulations, interviews and surveys. Within the scope of this thesis, the use of literature sources is chosen as a basis for the systems approach. Whereas measurements, simulations and case studies would require for a limited amount of devices or buildings to be selected in the early stages of research, the information obtained by means of a literature study is expected to expose the diversity that exists within the concept of intelligent building envelopes, and the variety of applications that can be found in the design and operation of intelligent building envelopes with regard to daylighting quality.

Two main literature sources are used for the collection of material, each of them offering a different kind of perspective and data: research papers and architectural magazines.

- **Research papers.** This type of source typically discusses particular solutions to meticulously defined problems, and thus constitutes a deliberate and separate study of the research field itself. Scientific articles are selected from the Science Direct online database, comprising all magazines published by Elsevier Science Ltd. All years of the following magazines are explored:

Annual Reviews in Control
Applied Energy
Artificial Intelligence
Automation in Construction
Building and Environment
Computers and Chemical Engineering
Control Engineering Practice
Decision Support Systems
Endeavour
Energy
Energy and Buildings
Energy Conversion and Management
Energy Policy
Engineering Applications of Artificial Intelligence
Environment International
Ergonomics
European Journal of Operational Research
Expert Systems with Applications
Futures
Fuzzy Sets and Systems
Information Sciences
International Journal of Industrial Ergonomics
Journal of Environmental Psychology
Journal of Non-Crystalline Solids
Journal of Personality and Social Psychology
Knowledge-Based Systems
Materials Today
Neural Networks
Remote Sensing of Environment
Renewable and Sustainable Energy Reviews
Renewable Energy
Sensors and Actuators A: Physical
Sensors and Actuators B: Chemical
Solar Energy
Solar Energy Materials & Solar Cells
Surface & Coatings Technology
The Journal of Systems and Software
Thin Solid Films

The following search terms are used:

Any combination of an adjective from the left column with a substantive from the right column:	
Active Adaptive Advanced (Double) Skin Dynamic Innovative Intelligent Interactive Responsive Smart Solar	Architecture Building Daylighting Design Strategies Envelope Facade
Additional search terms:	
Building Automation Building Performance Simulation Climate Envelope Climate Facade Curtain Wall	Dimmable Sensor Energy Optimisation Fuzzy Logic Occupancy Sensor Office Occupant

In addition, other scientific literature has been consulted for background information, often after having found a reference in the research articles.

- **Architectural magazines.** It is intriguing to explore how the ideas nurtured in scientific research are implemented in architectural projects. There is much to learn by studying concrete attempts to create solutions, when research and building practice join forces to create a solution specifically adapted to a particular case. This field experience may lead to the development of new products, in co-operation with the architect or design team, or to the adaptation of existing products to the framework given by a concrete site, function and climate. In this context, the main literature source for this thesis is the German magazine *Intelligente Architektur*, published by Alexander Koch GmbH. Appearing bimonthly, its scope comprises architecture, control systems and facility management. The magazine is chosen because of the architectural projects it presents. The *intelligent* principles that support the particular solutions chosen in material use, components, and composition are explained by members of the design team, along with the research that preceded the design of the architectural project.

1.6 Structure of the thesis

The thesis comprises six chapters, as depicted in Figure 1-2.

- **Chapter 1** introduces the reader to the particular field of research to be explored, identifies research questions, delineates the professional boundaries within which an answer will be sought, and describes the methods these answers are sought with.

- **Chapters 2** and **3** discuss the concepts of intelligent building envelopes and daylighting quality respectively. For each of the concepts, literature sources are used to identify a definition that fits the scope of this study, and to abstract characteristics that are expected to be fruitful for the system analysis performed in the subsequent chapters.

- In **Chapter 4**, it is analysed how an intelligent building envelope's adaptiveness - in the form of perception, reasoning and action processes - can be expected to perform functions related to daylighting quality.

- **Chapter 5** analyses the performance of a selection of physical applications in achieving the functionality described in Chapter 4, and the consequences the material use, form and composition of these physical applications have on their performance.

- **Chapter 6** summarises the findings made during the execution of this Ph.D. research, with regard to the research questions asked as well as the methodology used to answer them. In conclusion, recommendations are given for further research.

2 Intelligent building envelopes

2.1 The emergence of intelligent building envelopes

During the past few decades, buildings have been imposed to steadily increase their functionality at diminishing cost. In this context, the deployment of new and emerging technologies has lead to the use of the terms *intelligent building* and *intelligent building envelope* to describe a built form that can meet these demands, be it to a varying degree of success.

Frequently used in architecture, there exists a wide variety of definitions on the concept of *intelligent building envelopes*. Wigginton & Harris [2002], for example, list over thirty definitions of intelligence related to buildings and building envelopes. Simultaneously, this type of built form is denoted by terms like *adaptive*, *advanced*, *innovative*, and *interactive*. The multitude of terms and definitions opens for rather divergent interpretations of intelligence in building envelopes, and it may be discussed which term and definition is more appropriate in a given context.

Within the scope of this research, the intelligence of a building envelope is defined by its *ability to adapt to a variable environment by means of perception, reasoning and action*. This definition, to be elaborated in the course of this chapter, is based on the psychological development of intelligent behaviour in human beings. It is chosen because it relates the term *intelligence* to concrete psychical processes rather than to the more subjective and diffuse concepts of rationality, sensibility and good judgement often associated with human intelligence.

First, a literature brief will cite a selection of interpretations of intelligence in building envelopes; three groups are identified:

- Intelligent design, use and maintenance
- The use of artificial intelligence
- Responsiveness to the environment

This selection, however, does not provide sufficient information to answer the first part of the research question: "*What characterises intelligent behaviour for a building envelope?*"

Therefore, another path is explored. An additional literature review, on the psychological development of intelligence in humans, allows for the abstraction of relevant mechanisms for intelligent behaviour. The main topics of discussion among experts in the field are demarcated, and the characteristics of intelligent behaviour in humans delineated, with particular attention for the innate processes that procure such intelligent behaviour. These characteristics are then attempted transferred to a building envelope.

2.2 Defining intelligent building envelopes

2.2.1 Literature brief

Various definitions of intelligence in builing envelopes have been identified in literature, and classified into three groups:

- Intelligent design, use and maintenance
- Intelligent technology
- Responsiveness to the environment

As the three groups show considerable overlap, however, this should not be considered a strict taxonomy, but rather an indication of the variety that exists in this field.

2.2.1.1 Intelligent design, use and maintenance

A first group of definitions relates the intelligence of a building envelope, and architecture in general, to the skillfulness and rationality of the people who design, use and maintain it. A typical example of this type of definition is given by Kroner, who identifies three main areas of concern for *intelligent architecture* [1997:386-387]:

- **Intelligent design.** *"The design process must respond to humanistic, cultural and contextual issues; exhibit simultaneous concern for economic, political, and ecological sustainability at both the local and global scale; and, produce an artefact that exists in harmony with nature [...]"*
- **The appropriate use of intelligent technology.** *"Integrating intelligent technologies with an intelligent built form that responds to the inherent cultural preferences of the occupants is a central theme in intelligent architecture [...]"*
- **The intelligent use and maintenance of buildings.** *"For a design to be intelligent it must take into consideration the life cycle of a building and its various systems and components. Although an intelligent building may be complex, it should be fundamentally simple to operate, be energy and resource efficient, and easy to maintain, upgrade, modify, and recycle [...]"*

In this context, the intelligence of a building envelope is often linked to sensible goals such as energy efficiency, compliance with human needs, and the use of renewable energy sources: *"A glass facade can only then be properly described as "intelligent" when it makes use of natural, renewable energy sources, such as solar energy, air flows or the ground heat source, to secure a building's requirements in terms of heating, cooling and lighting. A wide range of energy saving measures can be implemented, such as natural ventilation, night-time cooling, natural lighting, the creation of buffer zones etc. This assumes an intensive interaction between the facade and the building"* [Compagno 1999:129].

Furthermore, intelligent design, use and maintenance is by many authors related to the building envelope's entire life cycle: the design and construction phase, the operational stage, renovation, re-use and demolishment [e.g., Clements-Croome 1997; Kroner 1997].

2.2.1.2 Intelligent technologies

An intelligent building envelope is often related to the use of *artificial intelligence* and building management systems; this was already briefly mentioned in the previous section, where Kroner identified the appropriate use of intelligent technology as one of the three main concerns for intelligent architecture. [Webster] defines *artificial intelligence* as:

- *"the capability of a machine to imitate intelligent behavior"*
- *"a branch of computer science dealing with the simulation of intelligent behavior in computers"*

Technologies based on artificial intelligence are becoming increasingly sophisticated and can be used for a number of purposes, such as automated control functions and diagnostic facilities. According to Kroner, intelligent technologies can be *"designed to signal deterioration of materials and components, incorporate auto repair capacities, and signal preventive and corrective maintenance"* [1997:387].

Also Selkowitz stresses the usefulness of intelligent technologies in the commissioning of buildings: *"New computer-based information systems will be used to commission buildings, to ensure that their day-to-day operation meets occupant requirements and over time meets evolving performance needs, and to help diagnose and even correct failures when they occur. Buildings have rarely had on-site skilled staff to operate them properly due to cost concerns. By installing extra sensors and controls in buildings, and linking them over the internet, the buildings of tomorrow can be continuously monitored and controlled by a trained staff from a remote location. The end result will be buildings that provide more effective living and working environments for people and place fewer burdens on the environment"* [1999:8].

Such technologies, however, also encompass the danger of becoming too complicated for the average user to understand or have control over their function and operation, in which case specialised personnel is needed to provide on-site technical assistance and training.

In addition, it is sometimes difficult to tell whether intelligent technologies have been deployed because of their functionality, or whether they merely are a part of an architectural high-tech expression of the building, also called *"toyerism"* [Kroner 1997:381] or *"the mere aestheticalisation of high tech"* [Kähler 1999:17].

2.2.1.3 Responsiveness to the environment

The manner in which the envelope is able to adapt to changes in its environment, is a third dimension of intelligence in building envelopes. Intelligence may be related to the *responsive performance* of the building envelope, *"the design and construction of which forms the single greatest potential controller of its interior environment, in terms of light, heat, sound, ventilation and air quality"* [Wigginton & Harris 2002:3].

In this context, an intelligent building envelope may be defined as *"a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort, by adjusting itself autonomically, with self-regulated amendments to its own building fabric [...] a flexible, adaptive and dynamic membrane, rather than a statically inert envelope"* [Wigginton & Harris 2002:27].

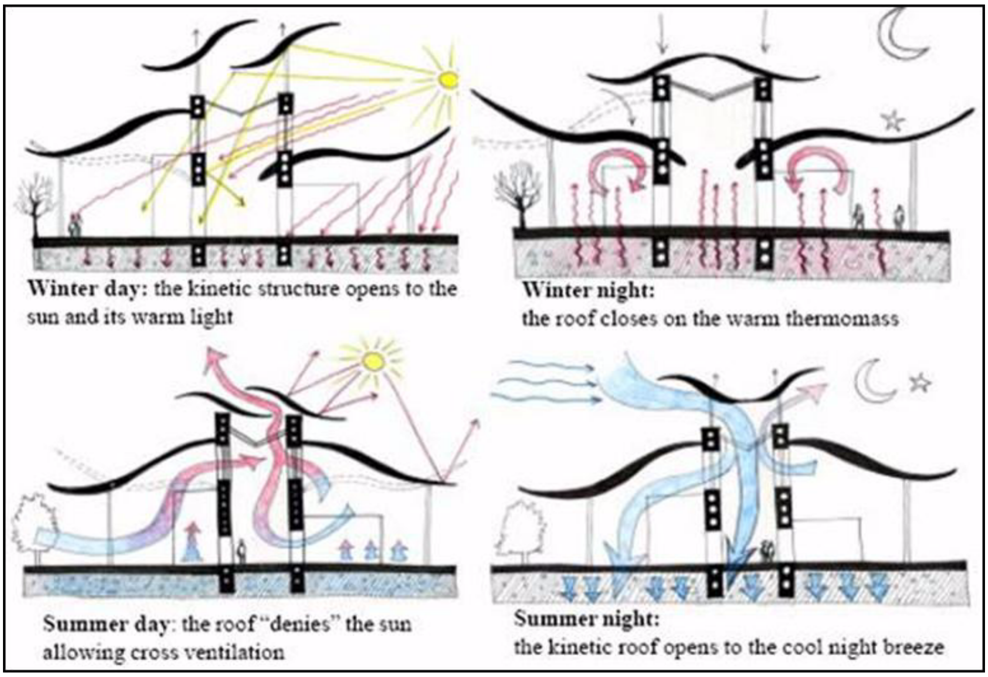
The ability of the building envelope to interact with its environment is even more important than the complexity of its control mechanisms; according to Compagno, *"an "intelligent" facade is not characterised primarily by how much it is driven by technology, but instead by the interaction between the facade, the building's services and the environment"* [1999:cover].

Of particular importance is the manner in which intelligent technology is able to adapt to the needs and preferences of the building users. Clements-Croome reports a frequent mismatch between the every-day performance of intelligent building envelopes and the expectations of the user, and argues that *"the intelligent building has generally been defined in terms of its technologies, rather than in terms of the goals of the organisations which occupy it. If the user is subservient to the technologies, this usually leads to situations where the technology is inappropriate for the users needs, and this can adversely affect productivity and costs"* [1997:398].

In search of a concept that can organise the building envelope into a coherent whole and adapt it to the intensity and quality of stimulation exercised by its environment, many designers turn to nature and its diversity of organisms for inspiration, so-called *biomimetics*. In this context, the built environment is often compared to an *ecosystem*, or *"a complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space"* [Britannica].

Tombazis points out animal and human skin as an ideal for the building envelope: being a highly versatile, multi-functional, multi-layered enclosure with self-healing and self-renewal capacities, natural skin has an immense variety and refinement, and is perfectly adapted to its environment. The dermis, the inner layer of human skin, is a *"tightly interwoven meshwork of strong and elastic fibres. It adapts to the movements of the body, it is thin and flexible over the joints, and thick and tough in other parts of our bodies"* [1996:53].

Magnoli *et al.*explore the design of DNA for responsive architecture (Figure 2-1), where *“the primary motivation of the design lies in creating a design solution that is flexible and adaptive at any scale, and at instances, responsive and intelligently active with respect to the changing individual and climatic contexts [...] As in any ecosystem, a fractal, coherent, continuous fluctuation at every scale of the system is vital”* [2001:4,8].



[Magnoli *et al.* 2001:7]

Figure 2-1: *A prototype for a biomimetic structure that is adaptive to changing climatic and individual contexts, designed by Magnoli* et al.

In *The Architecture of Intelligence*, a book that reviews effects of the IT revolution on architecture, de Kerckhove stresses that *“the skin is a tactile part of the body, not only something to look at, but also one of the most comprehensive systems of sensors that the body can boast of”* [2001:65]. The author refers to the work of several architects, among them Jean Nouvel and Toyo Ito, who actively explore the extended concept of building skin in their projects; Ito suggests that architecture *“as the epidermis must be pliant and supple like our skin and be able to exchange information with the outside world. Architecture clad in such a membrane should instead be called a media suit”* [*ibid.*].

2.2.2 Evaluation of results

It is found that this literature review does not provide sufficient information to answer the first part of the research question: *“What characterises intelligent behaviour for a building envelope?”*

The first group of definitions, regardless of the sensibility of its goals regarding *intelligent design, use and maintenance* of a building envelope, does not reveal any information regarding the skills required of an intelligent building envelope to fulfil those goals. In addition, this group of definitions ideally relates to all built structures, and particularly to traditional or vernacular architecture built in close connection with its environment.

The use of *intelligent technology* does not suffice to make a building envelope behave in an intelligent manner [Clements-Croome 1997; Compagno 1999; Kroner 1997]. Not only does this technology need to be used appropriately; ideally, it is also related to the envelope’s adaptation to and interaction with the environment and the user.

Responsiveness to change in the environment is a characteristic that approaches a description of intelligent behaviour; in addition, it refers to the abilities of the building envelope itself, rather than to those of the people who design and use it. The interpretations presented so far, however, do not provide any concrete information on how to achieve such adaptiveness, save frequent references to biomimetics.

2.3 Defining intelligent behaviour

In order to find out more about characteristics of intelligent behaviour, the path of human intelligence is explored. Based on a literature review of psychological research on the development of human intelligence, the following sections feature expert views on the characteristics of intelligent behaviour, and indicate points of accordance and divergence among them. Four characteristics are extracted as a common denominator for intelligent behaviour, and will in a next stage be attempted transferred to the building envelope:

- The ability to construct patterns
- The ability to solve problems
- The ability to adapt to the environment
- The ability to perceive, reason and act

2.3.1 Literature brief

What, above all, characterises *intelligent* behaviour? In comparison with similar terms such as *smart*, *clever*, *alert* and *quick-witted*, the term *intelligent* is *"stressing success in coping with new situations and solving problems." Intelligence* is described as *"the ability to learn or understand or to deal with new or trying situations [...] the ability to apply knowledge to manipulate one's own environment [...]"* [Webster]. The term *intelligent* is further related to both human and artificial intelligence:

- **Mental capacity.** *"having or indicating a high or satisfactory degree of intelligence and mental capacity"*
- **Skillfulness.** *"revealing or reflecting good judgement or sound thought: skillful"*
- **Intelligence.** *"possessing intelligence"*
- **Rationality.** *"guided or directed by intellect: rational"*
- **Artificial intelligence.** *"guided or controlled by a computer, especially: using a built-in microprocessor for automatic operation, for processing of data, or for achieving greater versatility"*

Lexical definitions use characteristics such as *the ability to cope with new situations, to solve problems* and *to apply knowledge to manipulate one's own environment* to describe intelligence.

In order to learn more about the mechanisms that induce such behaviour, expert literature on developmental psychology is consulted, and in particular the work of three psychologists: Jean Piaget, Pierre Oléron, and Pierre Gréco. While this literature mainly was published in the 1960's, it is in no manner outdated. In fact, this literature was chosen because of the frequent references of contemporary research to this source [e.g., Clements-Croome 1997; Hoff 2002].

2.3.1.1 The ability to construct patterns

Intelligent behaviour can be explained as a form of *structured interaction* between a subject and her environment. A subject does not respond randomly to stimuli in the environment, but rather acts according to certain patterns, the nature and complexity of which form an indication of the subject's intelligence [Piaget 1967].

The patterns a subject uses to respond to environmental stimuli are not rigid, but rather *flexible* and *multiform*. According to Oléron, *"a relatively wide range of stimuli can arouse an identical response [while] an identical stimulus may evoke perfectly distinct responses according to the existing constellation of the stimuli - or to their sequence"* [1969:4].

While flexibility and multiformity are characteristics of psychical processes in general, they are particularly marked in intellectual activity. According to Oléron, intelligent activity operates, above all, by means of *long circuits*: as opposed to the typical *reflex action,* where *“a response is immediately evoked by a stimulus according to a mechanism that is at once ready for action,”* intelligent activity is characterised by a *détour,* a *“long-circuit type of behaviour”* [1969:3].

The connections established between stimulus and response are flexible and multiform, but at the same time they exhibit *regularity*. According to Oléron, a subject does not react to a certain stimulus in itself, but rather to the interest that stimulus holds for the subject. Different stimuli can thus provoke the same response when they hold the same meaning for the subject, and this generates regularity.

Oléron connects this regularity to the use of *schemata* or *models*. A subject uses mental models to perceive objects and conditions in the environment and to act upon them. Those models are constructed and updated continuously in interaction with the environment, and they are the ones that provide regularity in the connection between stimulus and response. At the same time, however, the continuous updating of models in interaction with the environment also introduces new and varied elements into the stimulus-response cycle.

2.3.1.2 The ability to solve problems

Determining a clear demarcation line between intelligent activity and lower forms of psychical processes is subject to widespread disagreement among experts. As mentioned in the previous section, flexible and multiform stimulus-response patterns are particularly marked in intelligent activities, but do also exist as general characteristics of lower psychical processes. It can, however, be discussed which type of behaviour qualifies as intelligent: does basic sensori-motor adaptation suffice, or are learning skills or even insight and understanding required?

The difficulty of distinguishing between intelligent and lower forms of adaptation can be clarified by a discourse on the mechanisms of *problem solving*. Oléron defines a *problem* in the following manner: *“It may be said that in principle every situation to which a subject can not make appropriate response by drawing on his directly available repertoire or responses is a problem”* [1969:48-49]. He adds, however, two important qualifications:

- **The existence of a solution.** *“One can only speak of a problem when there exists a solution. The subject may find himself in a situation which it is completely impossible for him to overcome and which necessarily defeats him.”*
- **The use of intellectual means.** *“The solution must be obtained by intellectual means. If a subject succeeds in dealing with a situation simply by developing an automatically required ability or skill, it is merely a question of adaptation or learning [...] A cat which has been shut in a box and keeps on jumping until finally it succeeds in jumping high enough to get out, has not properly speaking solved a problem.”*

In order to respond intellectually to the environment, a subject must detect regularity in the stimuli presented by the environment and construct a mental model based on, and adapted to, those stimuli. Oléron explains how a subject can solve a problem in an intellectual manner by combining two sets of processes [1969:5-6]:

- **Induction.** *"The subject extracts, from data presented to him, regularities or constancies which are not immediately apparent."*
- **Subsumption.** *"[The] case, directly opposed to the first, [...] in which the appropriate schema is immediately applied to the stimuli: the subject fits them into the frame which is already at his disposal."*

Aided by induction and subsumption, a subject can solve a problem by means of several types of learning processes, varying from *groping* - learning by trial-and-error - to *insight*. Not all of these processes, however, are by experts accepted as intelligent behaviour. According to Gréco, insight has long been considered a distinctive criterion between intelligent behaviour on the one hand, and lower forms of learning, such as groping and sensori-motor adaptation, on the other hand [1969:208-209]:

- **Learning in the narrow sense.** *"the acquisition of new forms of behaviour by a series of trials involving the progressive elimination of errors"*, e.g. groping, trial-and-error
- **Intelligence.** *"the ability to resolve a problem immediately through a sudden and original reorganization or structurization of situations or responses"*, e.g. insight, understanding

The discussion on *groping* can be traced back to research performed by Thorndike since 1898. Studies of associative learning in animals, and problem solving in particular, led Thorndike to conclude that animals are not capable of higher processes of reasoning: *"The great majority of observed subjects did not discover the solution to the problem. All that happens is that the time taken to release the mechanism decreases from one trial to the next and the number of unnecessary movements and gestures diminishes slowly and irregularly"* [Gréco 1969:210].

According to Thorndike, however, the distinction between groping and insight does not necessarily lead to a discontinuity; these processes may rather be seen as an extension of each other. Also Piaget considers groping and insight to be part of the same process; rather than aiming to draw a lower demarcation line for intelligence, he argues, it should be thought of as a continuum: *"Intelligence itself does not consist of an isolated and sharply differentiated class of cognitive processes. It is not, properly speaking, one form of structuring among others; it is the form of equilibrium towards which all the structures arising out of perception, habit and elementary sensori-motor mechanisms tend"* [1967:6].

2.3.1.3 The ability to adapt to the environment

In the previous section, intelligent behaviour was explained to be a form of structuring of a subject's interaction with the environment. This type of interaction, according to Piaget, is always characterised by *adaptation*: *"Every response, whether it be an act directed towards the outside world or an act internalized as thought, takes the form of an adaptation or, better, of a readaptation [...] The individual acts only if he experiences a need, i.e., if the equilibrium between the environment and the organism is momentarily upset, and action tends to re-establish the equilibrium"* [1967:4].

Adaptation, in this context, needs to be interpreted as *"an equilibrium between the action of the organism on the environment and vice versa"* [Piaget 1967:7]. This corresponds to [Webster], who defines *adaptation* as:

- *"adjustment of a sense organ to the intensity or quality of stimulation"*
- *"modification of an organism or its parts that makes it more fit for existence under the conditions of its environment"*

Defining intelligence in this manner, one runs the risk of ending up with a very general description, including a wide range of cognitive processes. According to Piaget, however, it is more important to take care of the continuity that exists in the range of psychical processes, than to draw an arbitrary demarcation line. Intelligence, in this respect, needs to be thought of as *"an extension and a perfection of all adaptive processes"* [1967:9].

In short, one can say that *"behaviour becomes more "intelligent" as the pathways between the subject and the objects on which it acts cease to be simple and become progressively more complex"* [Piaget 1967:10].

2.3.1.4 The ability to perceive, reason and act

If *intelligence* is interpreted as structured interaction with the environment by means of a continuum of psychical processes, ranging from understanding and insight to learning and groping, the question remains as to how such intelligent behaviour is made to emerge in subjects.

According to Piaget, *"perception, sensori-motor learning (habit, etc.), an act of insight, a judgment, etc., all amount, in one way or another, to a structuring of the relations between the environment and the organism"* [1967:5]. In interacting with the environment, the subject perceives stimuli in that environment, generates an appropriate response based on its current mental models of that environment, and executes that response. Simultaneously, the subject's mental model is updated in this interaction with the environment.

This behaviour allows the subject to adapt to the intensity and quality of stimulation exercised by the environment, to solve problems and to cope with new situations in the environment. Problem solving may occur by means of insight and understanding when the problem suddenly is structured in the right form. It may, however, also occur by means of a series of successive structuring and restructuring until the right pattern is found, in other words a process of learning or groping. The latter, however, is not by all experts acknowledged as intelligent behaviour.

2.3.2 Evaluation of results

Having identified psychical processes that procure intelligent behaviour in humans, it remains to be discussed whether these mechanisms can be transferred to a building envelope. In order to assess the relevance of such a transfer, another literature search is performed, aiming to find descriptions of adaptiveness by means of perception, reasoning and action in the field of building design and related topics, such as control systems and artificial intelligence.

In the field of artificial intelligence, several definitions relate intelligent behaviour to the ability to perceive, reason and act. de Silva, for example, interprets intelligence as structured information, acquired by a system through experience and learning; in this respect, intelligent systems are able to *"acquire and apply knowledge in a proper (intelligent) manner and have the capabilities of* perception, reasoning, learning, *and making inferences from* incomplete information*"* [1995:24].

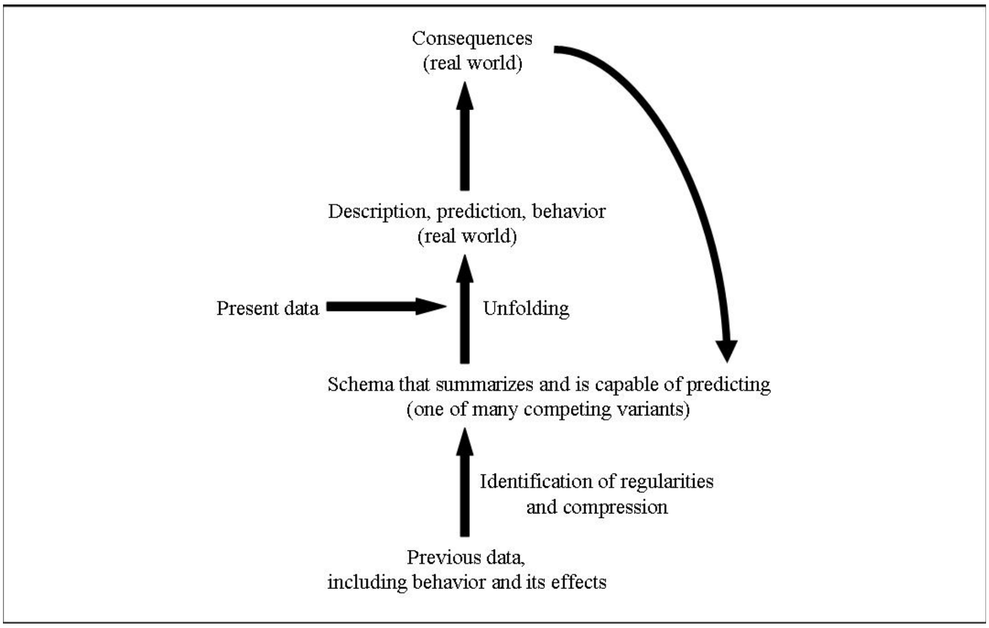
A similar definition is presented by Fleming & Purshouse, stating that *"an intelligent system can make appropriate, autonomous, decisions and generally incorporates a process of learning (although no firm definition of such a system exists)"* [2002:1230].

Hayes-Roth describes an intelligent system that continuously and simultaneously performs three functions [1995:329]:

- **Perception.** *"perception of dynamic conditions in the environment"*
- **Reasoning.** *"reasoning to interpret perceptions, solve problems, draw inferences and determine actions"*
- **Action.** *"action to affect conditions in the environment"*

In a similar manner, Gell-Mann, describes the operation of a complex adaptive system by means of the flow of information from data via cognition to a response (Figure 2-2). According to the author, a complex adaptive system [1995:17]:

- *"acquires information about its environment and its own interaction with that environment"*
- *"identifying regularities in that information"*
- *"condensing those regularities into a kind of "schema" or model"*
- *"and acting in the real world on the basis of that schema"*



From [Gell-Mann 1995:25]

Figure 2-2: *The operation of a complex adaptive system.*

Hayes-Roth further stresses that responsiveness to change in the environment is not necessarily met by just one sequence of perception, reasoning and action. A system may be presented with a wide range of situations of different intensity and quality, and one particular set of perception, reasoning and action may not be equally fit for every condition that is likely to occur in the environment. It is, therefore, desirable for a system to have a range of perception, reasoning and action strategies to choose from, according to circumstances. This can be related to the flexibility and multiformity of psychical processes that procure intelligent behaviour, as discussed in Section 2.3.1.

Within the field of architecture, the ability to perceive, reason and act is, amongst others, brought up by Kroner, who refers to intelligent architecture as *"built forms whose integrated systems are capable of anticipating and responding to phenomena, whether internal or external, that affect the performance of the building and its occupants"* [1997:386].

According to Beukers & van Hinte, *"a 'smart' material (or system or structure - the one word takes all) interacts with its environment, responding to changes in various ways"* [1998:44-45]. They distinguish between three levels of *smartness*, according to the manner in which a material, structure or system responds to the environment [*ibid.*]:

- **Reflex action.** *"smartness can be a simple response which follows on directly and inevitably from the stimulus"*
- **If-then construct.** *"the outcome of an if-then construct in which a decision is made based on balancing the information from two or more inputs"*
- **Learning ability.** *"the ability to learn, which is probably the smartest thing of all, since learning can lead to a patterned model of the world (the brain is 'stored' environment') allowing informed prediction"*

It is found that several definitions regarding intelligent systems and structures can be related to responsiveness to changes in the environment and the ability to perceive, reason and act - characteristics that in Section 2.3.1 were described as intelligent behaviour. The results of the literature brief indicate that a similar approach is relevant for describing intelligent behaviour for a building envelope.

2.4 Defining intelligent behaviour for building envelopes

2.4.1 An operational definition

Section 2.3 leads to the following operational definition for an intelligent building envelope:

> An intelligent building envelope adapts itself to its environment by means of perception, reasoning and action. This innate adaptiveness enables the envelope to cope with new situations and solve problems that may arise in its interaction with the environment.

This definition does not automatically link an intelligent building envelope to the achievement of specific goals, but rather depicts the skills and behaviour to be expected from an intelligent building envelope in order to attain those goals.

2.4.2 Objectives for an intelligent building envelope

Given its characteristic processes of perception, reasoning and action, three main objectives are considered to be particularly relevant for an intelligent building envelope to fulfil in its interaction with the environment:

> - The ability to handle variation
> - The ability to handle conflict
> - The ability to handle occupant behaviour

2.4.2.1 The ability to handle variation

Adaptiveness ideally enables an intelligent building envelope to cope with new and varying situations in its environment. This environment can be regarded as composed of three main elements:

- An outdoor element with climate and site conditions
- An indoor element contained within the shell of the building envelope
- An element consisting of the building users, their preferences and behaviour

Within this environment, an intelligent building envelope needs to be able to provide an acceptable response to regular variations, unanticipated events, and changes in priorities and performance criteria. In addition, the envelope needs to take into account changes in its own performance due to, for example, the ageing of equipment, the accumulation of dust, and the breakdown of components.

In order to provide this response, an intelligent building envelope needs to be designed with a flexibility that allows it to implement various strategies and to adjust its physical layout accordingly. In designing the envelope, however, it is not possible to anticipate every situation that may arise, create an exhaustive list of requirements, and determine the morphology of the building envelope accordingly. In order to be able to respond to a wide range of real-time situations, therefore, an intelligent building envelope ideally is able to manage its own strategies and layout as the need for adaptation arises.

2.4.2.2 The ability to handle conflict

In a dynamic and intricate environment, the tasks required of a building envelope are sometimes conflictive; trade-offs need to be made according to an appropriate set of priorities. Simultaneously, there may exist several manners in which to handle a particular task, each of them pursuing the same objective, though with different side effects. An intelligent building envelope ideally is able to anticipate the effect a chosen action will have on all of the tasks it needs to perform, and include this in its consideration of multiple, conflictive performance criteria in search of an optimal solution.

Governing a complex set of priorities and performance criteria requires for an intelligent building envelope to be flexible in its strategies and morphology. A flexible layout will provide the building envelope with more manners in which to perform a certain task and increase its chances of finding the most favourable solution to a given set of problems. Multiple chains of perception, reasoning and action make it possible for the envelope to adapt strategies as required by the situation at hand.

2.4.2.3 The ability to handle occupant behaviour

The building occupant forms a particular point of focus in the variable and conflictive requirements an intelligent building envelope needs to handle. Ideally, an intelligent building envelope is able to adapt to user needs, preferences and behaviour, and the effects of their presence.

There exist considerable differences in needs and preferences among individuals, which may diverge significantly from average users' needs stated in standard building regulations [IEA 2000]. Such variations are due to differences in the position of the workspace and the tasks to be performed, individual preferences, and clothing and metabolic levels [Selkowitz 1999].

In addition, the occupants' feeling of control over the work environment is of the utmost importance. In a study on user satisfaction with lighting control systems, for example, Velds [1999] found the inability to overrule the system to be the users' most important complaint with respect to the control systems.

The occupants' ability to take adaptive action will influence their overall feeling of comfort and satisfaction [Baker & Steemers 2000]. Providing building occupants with the opportunity to adapt their work environment even seems to expand their comfort zone [Garg 2001]. Dissatisfied users, on the other hand, may actively counteract control strategies, and even try to sabotage their operation. According to Fitzgerald & Fitzgerald, *"the most probable cause of a system's failure is people. By this we mean the non-acceptance of the system and, therefore, the philosophy and method of going around or "beating" the system"* [1987:248].

The nature and extent of control given to the building occupant needs to be considered carefully; while the right type of control increases the occupant's comfort and satisfaction, other types may cause stress and dissatisfaction instead. Important, according to Burger, is the occupants' *"perceived ability to significantly alter events [...] It is the* perceived *level of control that appears to have determined the response"* [1989:246]. In this context, Averill [1973] distinguishes between three different types of control:

- Decisional control
- Cognitive control
- Behavioural control

Decisional control is related to the availability of choice in the physical environment. Giving the building occupant the opportunity to make various adjustments, such as the availability of thermostats and Venetian blinds, has in several studies been reported to increase the occupant's comfort and satisfaction, even when the adaptive action is not taken [Baker & Steemers 2000; Garg 2001].

Cognitive control is related to the occupant's perception of control, or the awareness that her preferences determine outcomes in the indoor environment. While also this type of control is reported to contribute to user satisfaction, there is a great number of uncertainties, particularly with regard to the specific conditions that influence cognitive control. In a study performed by Veitch & Gifford [1996], for example, it is attempted to separate the availability of choice (decisional control) from the experience of preferred environmental conditions (cognitive control). It is hypothesised that a building occupant may feel in control by obtaining conditions that she prefers, without having had the opportunity to choose those conditions. However, the results show that while the availability of choice increases the occupant's perception of control, it simultaneously leads to a decrease in occupant performance.

Behavioural control concerns those conditions where the building occupant needs to make adjustments by herself in order to avert a threatening event, such as the avoidance of glare and overheating. This type of control may induce frustration if the occupant constantly feels the need to override the control system, and may, in addition, cause the occupant to feel fear of failure or making a 'wrong' decision. Therefore, behavioural control is often found to decrease occupant satisfaction [Veitch & Gifford 1996].

In order to cope with the difficulty of providing the occupant with the right nature and extent of control, Willey [1997] proposes a distinction between *situation states* and *control states*. Building occupants are able to state their preferences regarding environmental conditions (situation state), but are not able to decide how these conditions will be achieved (control state).

In addition, the user can be informed of the intended system performance and taught how to use the controls, in order to lessen the fear of making a 'wrong' choice; including the users in the design process of the controls may further increase their feeling of control [IEA 2001; Veitch & Gifford 1996].

2.4.3 Functional characteristics

This section discusses the three functional characteristics that enable an intelligent building envelope to adapt to a dynamic and intricate environment:

- Perception
- Reasoning
- Action

2.4.3.1 Perception

An intelligent building envelope ideally is able to obtain information regarding conditions in the environment and its own interaction with that environment:

- **The outdoor environment.** Climate and site conditions
- **The indoor environment.** Surface characteristics, furnishings and equipment, indoor climate, fire detection and security
- **The building occupants.** Their absence and presence, behaviour and preferences, and the effect of their activities, such as perspiration and the use of equipment
- **Envelope performance.** The behaviour of equipment, deterioration of materials and components, and the need for maintenance; in addition, feedback on the results of envelope strategies: do they lead to the appropriate result, and what are the side effects?

This can be achieved by means of *sensory perception*, or *“the transformation of data from sensors into meaningful and useful representations of the world. Sensory perception accepts input data from sensors that measure states of the external world as well as internal states of the system itself”* [Albus 1999:4].

Multiple sources may be combined to produce more accurate and reliable information out of noisy and incomplete data. This, however, also increases the complexity of the system that is to turn these data into information [de Silva 1995].

There is no possibility for an intelligent building envelope to perceive and process every detail in the environment, as the envelope’s morphological and computational resources are bound to be finite. The type and amount of data to be acquired by the envelope thus need to be considered carefully for their accuracy and relevance with regard to the envelope’s performance criteria and objectives, and the time the envelope requires to process and react to this information.

Sensory perception ideally documents the state of the environment and the performance of the envelope in real-time, allowing the envelope to fine-tune its operation to environmental conditions as they occur; it may even be used to identify and track objects in the environment. In addition, the envelope needs to monitor the performance of its own component parts in order to ensure optimal operation, and to identify the occurrence of faults and other unfavourable events, such as the incidence of unanticipated problems during task performance.

The envelope is faced with a particularly intricate challenge in monitoring the building occupant. A first issue is the occupant’s absence or presence, as this determines the degree to which comfort requirements are to be taken into account. A second type of occupant information the envelope needs to obtain, regards the specific needs and preferences of each of the occupants present, related to factors such as task performance, occupant position, individual preferences, and weather conditions.

Sensory perception may occur by means of any device or material that measures or in another way is able to discern environmental conditions. Examples are:

- Materials sensitive to, for example, heat or light
- Sensors connected to the building, such as photocells on the facade or indoors
- User interfaces
- Measuring stations, for example on floor levels or on top of the roof
- Remote sensing by means of geostationary satellites

Several of these applications will be discussed in Chapter 5.

2.4.3.2 Reasoning

There are various reasoning skills an intelligent building envelope may apply to optimise its interaction with the environment:

- Processing information from multiple sources into an optimal solution
- Anticipating environmental conditions
- Learning occupant preferences
- Anticipating the outcome of envelope actions

Without these particular reasoning skills, adaptation to the environment typically occurs by means of a reflex action, or *"a simple response which follows on directly and inevitably from the stimulus"* [Beukers & van Hinte 1998:45].

The reasoning skills of an intelligent building envelope aim to combine the advantages of artificial intelligence - a powerful information processing tool - with favourable characteristics of human intelligence. de Silva [1995] highlights the following ones in particular:

- Flexibility
- Adaptiveness to unfamiliar situations
- Efficiency in gathering information, discarding irrelevant details

In short, *"the information which is gathered need not be complete and precise and could be* general, qualitative, *and* vague *because humans can reason, infer, and deduce new information and knowledge. They have common sense. They can make good decisions, and also can provide logical explanations for those decisions. They can* learn, perceive, *and improve their skills through experience"* [de Silva 1995:2].

Learning abilities are of the utmost importance to an intelligent building envelope: the appropriate manner in which to react to environmental conditions and individual occupants may vary from case to case, and thus, ideally, the envelope is able to learn desired solutions for each case. In addition to a *"large memory capacity and fast "number crunching" abilities"* [Kasabov & Kozma 1998:455], a learning, adaptive system should have the ability to [Hagras *et al.*2003:34]:

- *"adapt and generate its own rule (rather than being restricted to simple automation)"*
- *"accommodate in an incremental way any rules that will become known about the problem"*
- *"learn and improve through active interaction with the user and the environment"*
- *"analyse itself in terms of behaviour, error and success"*

Learning ideally occurs in real-time (whenever new information is retrieved) and on-line (while simultaneously performing its other functions). A long reaction time, without any form of feedback from the envelope, is likely to irritate the building occupant. In order to optimise the system's adaptation to a variable environment, the ability to learn is ideally accompanied by *"storage and retrieval capacities"* and *"parameters to represent short and long term memory, age, forgetting, etc."* [Hagras *et al.* 2003:34].

Unfortunately, real-time and on-line learning is, for the time being, very demanding. Alternatively, an intelligent building envelope can store new information for a certain amount of time without processing it, and update its memory for example during the night, in order to apply it the next day [Guillemin & Molteni 2002].

Also the ability to predict and anticipate events is desirable for an intelligent building envelope. Being able to predict the occurrence of disturbing environmental conditions as well as the outcome of its own actions - not only the main (intended) effects, but also the (unintended) side effects - ideally allows the envelope to:

- Make informed decisions
- Prevent disturbing conditions instead of merely reacting to them
- Elaborate long-term strategies that minimise the occurrence and impact of future disturbances

Reasoning skills as described above need to be supported by a specific type of information technology, in order to obtain the adaptation and operation time that is required in the envelope's interaction with the environment.

Conventional, model-based control algorithms, according to de Silva [1995] and Garg [2001], are unfit to induce this type of intelligent behaviour. While they may successfully be applied when a mathematical model exists for the system to be controlled, the operation of an intelligent building envelope involves factors that are difficult to fit into a mathematical model, such as a high degree of non-linearity and a large number of parameters. This type of algorithms does not *understand* environmental conditions that do not accurately fit the model, and is thus unable to respond properly.

Soft computing, on the other hand, a concept introduced by Zadeh, encompasses a number of technologies that *are* able to function effectively in imprecise and uncertain environments [Medsker 1995]. Inspired by processes related to human intelligence, soft computing includes technologies such as:

- Expert systems
- Artificial neural networks
- Fuzzy systems
- Evolutionary algorithms
- Case-based reasoning

In Chapter 5, the characteristic weaknesses and strengths of these technologies and their hybrids will be discussed, along with a selection of their applications in daylighting quality.

2.4.3.3 Action

The morphology of a building envelope strongly limits its potential adaptiveness to the environment. When elaborating an appropriate response in reaction to environmental conditions, an intelligent building envelope needs to take into account the nature and extent to which the following of its components' characteristics are adaptable:

- Material characteristics
- Formal characteristics
- Compositional characteristics

The adaptiveness of these characteristics for daylighting purposes is to be discussed in further detail in Chapter 5.

Important is not only the type of adaptation the envelope undertakes, but also its timing and extent. Appropriate timing for the execution of a response depends on the type of event that initiated the response.

Responding to the building occupant's instructions should, in general, take as little time as possible. If the requested action can not be performed immediately, the envelope should at least acknowledge having received and understood the message, otherwise, "*delays in feedback will create an erroneous impression the system is not working. For example, a green light could go on indicating that the requested preferences or options were received by the computerized system. Additional information, indicating the response of the system to the commands of the user (i.e., a 'smart response'), would also be helpful*" [Vine 1998:217].

Responding to potentially disturbing environmental conditions, on the other hand, requires a different approach. Preventive action may be taken in order to attenuate or stop an event from occurring. Alternatively, the envelope can wait for a disturbing situation to arise before correcting it. A third option is not to respond at all - reacting to every change in the environment, too often, too quickly or on too large a scale, may prove to be just as disturbing to the building occupant as not reacting at all.

Having found and executed an appropriate response, the results of the action can be fed back to the envelope in order to influence the subsequent reasoning process. As mentioned earlier, some circumstances may require a kind of *reflex action*, where perception immediately triggers action, and reasoning is omitted.

2.4.4 Morphological consequences

Envelope morphology, in this context, refers to the set of components that induce adaptive behaviour, their functionality, the manner in which they are organised within the building envelope, and the connections and interaction that exist between them.

A wide variety of adaptive materials and components may be applied in an intelligent building envelope. They may be application-specific, or instead be able to fulfil several functions simultaneously or consecutively. While the latter may complicate the component's design and functionality, it also reduces the number of individual envelope components and their interconnection.

In this context, some emphasise the importance of *architectural parsimony*, and state that *"a compelling architecture should minimize the number of component mechanisms with which it supports the several required forms of adaptation"* [Hayes-Roth 1995:359].

Important is not only the type of adaptiveness the components support, but also the manner in which they are designed for integration or co-operation with each other, at different levels of scale - workspace, room and building level. An appropriate combination of elements, applied at the appropriate scale, may further adaptiveness, decrease conflicts among tasks and devices, and enhance areas of synergy. Three characteristics in particular will be discussed in further detail:

- Modularity
- Hierarchy
- Connectivity

2.4.4.1 Modularity

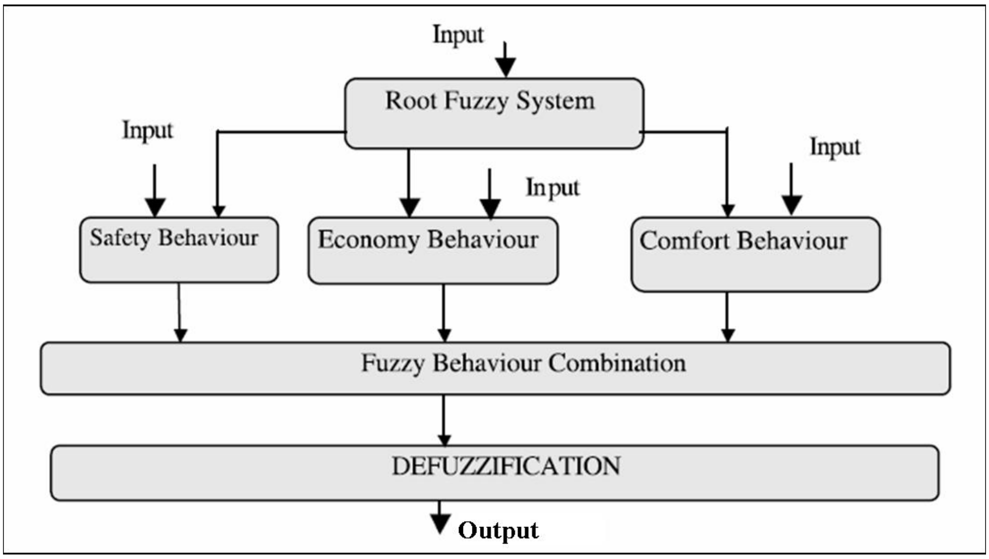
The manner in which the various components and the spatial and functional relations in between them are organised, has implications for the efficiency of an intelligent building envelope as a whole. Layering of functions reduces interdependencies between the distinctive components and makes them more easy to operate. It also simplifies the addition of new layers or subsystems without significantly modifying the system software [Albus 1999].

The envelope may be composed of loosely-coupled modules, where the individual components are easily substituted and appended; alternatively, the envelope may appear as a tightly integrated whole, where every component is essential, as is its consistent integration in the design and operation of the envelope. In practice, the envelope will be composed of a mixture of these two extremes.

Modularity may be based on a functional division of tasks between several components. Additionally, strategies may be organised into control modes, related to distinct types of situations; splitting up behaviours into modules that are relatively autonomous, allows for them to be optimised independently more easily [Choi *et al.* 2001].

Hagras *et al.*, for example, describe a control system with a behaviour divided into four modules, each of them responding to a specific type of situation (Figure 2-3) [2003:39]:

- **A safety behaviour.** *"ensures that the environmental conditions in the room are always at a safe level"*
- **An emergency behaviour.** *"in the case of a fire alarm or another emergency, [this function] might for instance open the emergency doors and switch off the main heating and illumination systems. In the case of an emergency this will be the only active behaviour"*
- **An economy behaviour.** *"ensures that energy is not wasted so that if a room is unoccupied that heating and illumination will be switched to a sensible minimum value"*
- **A set of comfort behaviours.** *"ensure that the conditions the occupant prefers (subject to being safe) are set. The learning process is done* interactively*"*



From [Hagras *et al.* 2003:38]

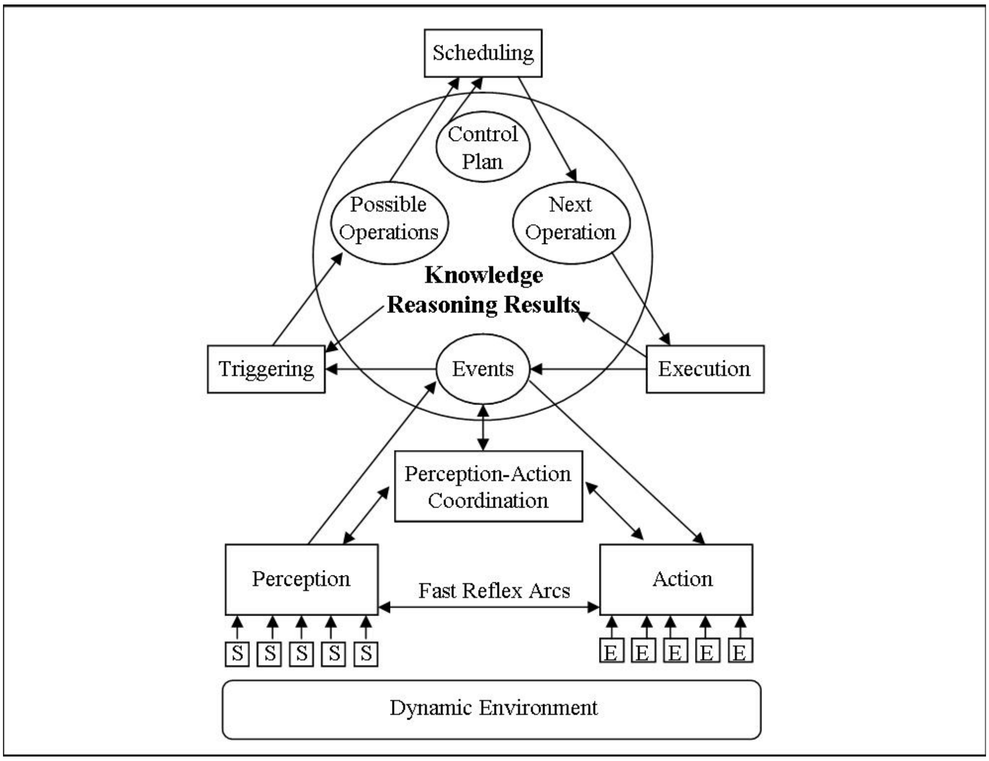
Figure 2-3: *A control system developed by Hagras* et al.*, with a behaviour divided into four modules, each of them responding to a specific type of situation.*

2.4.4.2 Hierarchy

In order to coherently link the various modules into a well-functioning whole, components, tasks and goals need to be organised into hierarchical layers. Higher levels typically have a broader spatial and temporal horizon but less detail, while the lower levels cover a narrower field but focus more on details. According to Hagras *et al.* [2003], a hierarchical approach decreases the complexity of the control rule base and reduces the resources needed for processing information.

One example of a hierarchical approach was depicted in Figure 2-4. Each of the modules first provides recommendations to optimise its own behaviour; these recommendations are then integrated to optimise the operation of the entire system by means of *fuzzy logic*, a type of soft computing that is to be discussed in Chapter 5.

Figure 2-4 shows another example, where components for perception, reasoning and action are organised in a hierarchical system. Hayes-Roth explains: "*Perception processes acquire, abstract, and filter sensed data before sending it to other components. Action systems control the execution of external actions on effectors. Perception can influence action directly through reflex arcs or through perception-action coordination processes. The cognition system interprets perceptions, solves problems, makes plans, and guides both perceptual strategies and external action. These processes operate concurrently and asynchronously [...] Perception-action operations occur at least an order of magnitude faster than cognitive operations*" [1995:334-335].



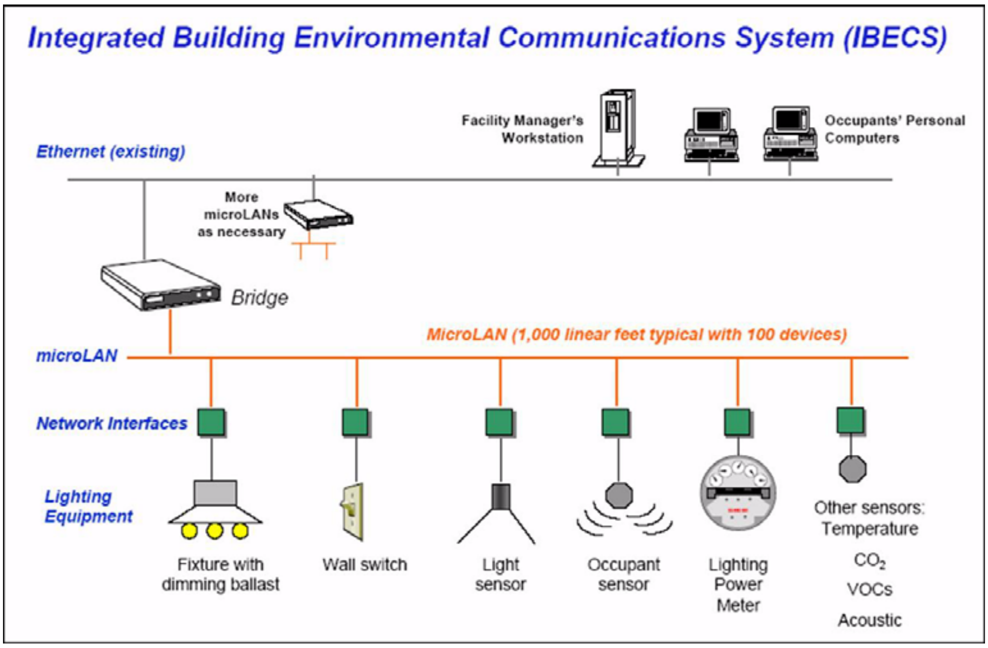
From [Hayes-Roth 1995:334]

Figure 2-4: *A hierarchical organisation of component systems for perception, reasoning and action processes.*

2.4.4.3 Connectivity

In order to co-ordinate and synchronise coinciding processes of perception, reasoning and action, communication between the various system components is of vital importance. In this context, *connectivity* can be defined as *"the ability to connect to or communicate with another computer or computer system"* [Webster], and denoted by *"the nature of the topology of the network connecting the sensors to the central processor"* [Brignell & White 1999:251].

Connectivity between the components of an intelligent building envelope is enabled by communication technology and infrastructure through which information and resources can flow. In order to be able to communicate with each other, the envelope components must show considerable conformity and compatibility; drives and controls from various manufacturers need to be connectable. Figure 2-5 shows an example of a building communications system, as designed by Lee *et al.* [2004].



[Lee *et al.* 2004:505]

Figure 2-5: *Diagram of an Integrated Building Environmental Communications System (IBECS)*

3 Daylighting quality in non-domestic buildings

3.1 Daylighting for human needs

The appropriate admission and distribution of daylight in the built environment offers the potential to accentuate architectural form, to provide a stimulating, comfortable and healthy indoor environment, and to contribute significantly to energy conservation in buildings. *Appropriateness* in this respect depends on a variety of perspectives such as human experience, ecology, aesthetics, functionality, energy efficiency, and flexibility. In addition, the design of daylight apertures in the building envelope exerts a significant influence on the external architectural expression of the building.

Most of all, however, daylighting the built environment serves people. During the past few decades, people have come to spend an increasing amount of time working and living in artificial light. According to Brainard [1995], several studies indicate that such practice causes workers to suffer from a deficit of daylight exposure, which gives rise to detrimental physiological and psychological effects. The recognition of these effects has promoted research on the identification of factors in the luminous environment that influence human behaviour and preferences, and on the nature and extent of the interaction that occurs between these factors. This topic is further addressed in Section 3.3. First, general characteristics of daylight as a light source are discussed, and outcomes of daylighting non-domestic buildings are delineated.

3.2 Daylighting non-domestic buildings

Four decades ago, Hopkinson *et al.* [1966:xxxii] pointed out two main objectives for daylighting buildings:

- *"to provide sufficient illumination for work to be done efficiently, quickly, and without error"*
- *"to provide a pleasant visual environment"*

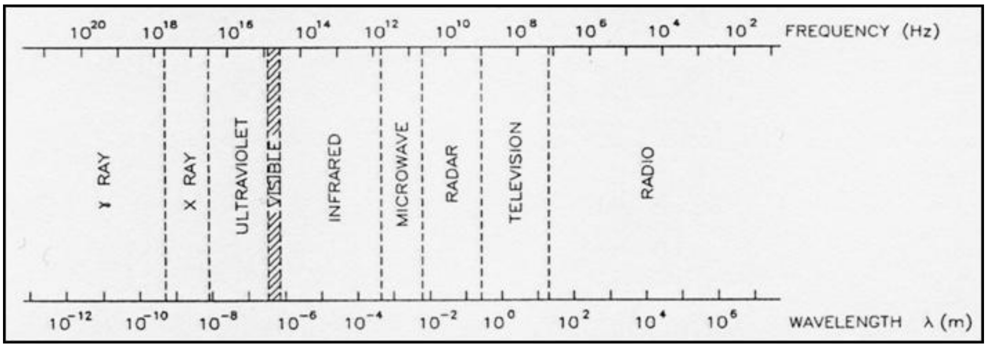
Despite a tremendous evolution in artificial lighting systems, daylight's role in attaining these objectives seems to only have increased since. Section 3.2 describes the particular characteristics of daylighting the indoor environment, and their relevance for human perception. In addition, the outcomes of the use of daylight in non-domestic buildings is discussed in short, with primary focus on human, energy and financial issues.

3.2.1 Daylighting properties

Daylight is collected, admitted and guided into the indoor environment by means of *daylight apertures* in the building envelope; the material, form and location of these apertures thus plays a decisive role in the successfulness of a particular daylighting design, i.e., having daylight penetrate the building envelope where wanted, and distribute it appropriately. Simultaneously, daylight apertures need to satisfy what is assumed to be another basic human need: contact with the natural environment.

3.2.1.1 Daylight as a light source

From a strictly physical point of view, daylight is defined as *"the part of the energy spectrum of electromagnetic radiation emitted by the sun within the visible wave-band that is received at the surface of the earth after absorption and scattering in the earth's atmosphere"* [Baker *et al.* (ed.) 1993:2.7].



[Serra 1998:117]

Figure 3-1: *The radiant spectrum; visible radiation has a wavelength between 380 and 780 nm.*

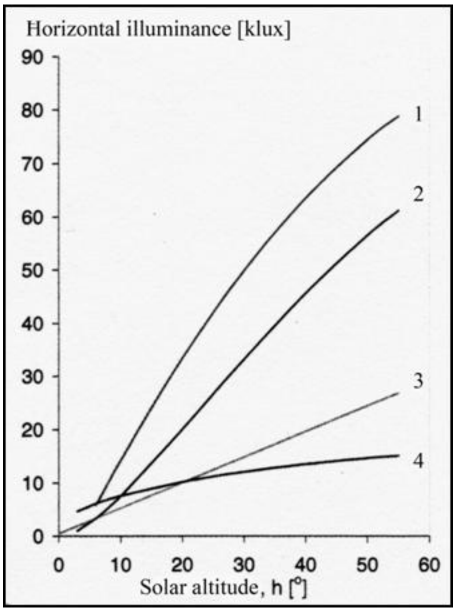
Daylight thus refers only to the part of solar radiation that causes a visual response in humans, more specifically direct and diffuse solar radiation with a wavelength between 380 nm and 780 nm (Figure 3-1) [CIE 1987]. Precise limits, however, depend on the visual acuity of the human eye and the intensity of radiation reaching the retina [Baker *et al.* (ed.) 1993].

In the indoor environment, daylight is composed of a mixture of direct sunlight, diffuse skylight, and their reflection off in- and outdoor objects and surfaces they encounter on their path to the indoor environment. Two main types of daylight sources may be distinguished [Hopkinson *et al.* 1966]:

- **Primary sources of daylight.** Sources that emit daylight, i.e., sun and sky.
- **Secondary sources of daylight.** Surfaces that reflect but do not emit light, i.e., surfaces and objects in the in- and outdoor environment, whose brightness is the result of the reflection of daylight.

The sun is a concentrated light source whose radiation is scattered, absorbed and reflected before reaching Earth; only part of the radiation penetrates the built environment in the form of direct beam illumination. The intensity of solar radiation depends on the position of the sun and the thickness of the air mass the light passes through in the atmosphere, and varies for all orientations and points in time. Direct sun may illuminate a horizontal plane up to 100,000 lux [Lyskultur 1998].

The sky, on the other hand, forms an extensive diffuse source of daylight. Varying with solar height and the density and movement of clouds, sky luminance may reach up to 10,000 cd/m^2 on overcast days, and even higher in case of bright sunlit clouds [Baker *et al.* (ed.) 1993]. For a solar angle of 50^o, diffuse skylight may illuminate a horizontal plane up to 25,000 lux on overcast days, while around 14,500 lux in case of a clear sky (Figure 3-2) [Lyskultur 1998].



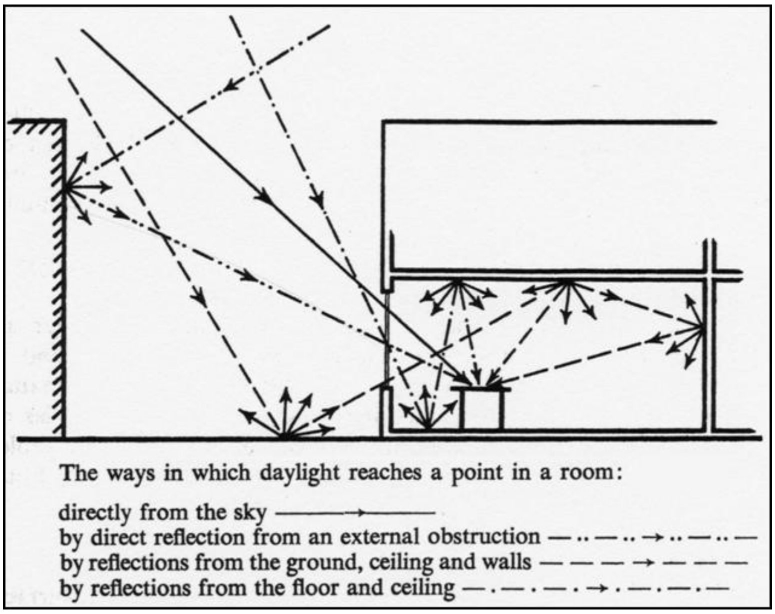
From [Lyskultur 1998:19]

Figure 3-2: *Outdoor illuminance on a horizontal surface, as a function of solar altitude in different sky types: (1) clear sky with sun; (2) partially overcast sky; (3) overcast sky; (4) clear sky.*

Daylight is a light source with high luminous efficacy, delivering full-spectrum light and perfect colour rendering. In the course of evolution, the human eye has adapted to daylight as the main source of light, and daylight is therefore considered to be the light source that provides the best preconditions for a good visual response.

Daylight is, however, also a highly variable light source, with strong local and regional characteristics. Its intensity, directionality, spectral distribution and colour temperature display temporal and spatial variations according to the specific combination of diffuse skylight and direct sun daylight is composed of [Chain *et al.* 2001]. Some of these changes are predictable and follow circadian and seasonal rhythms, such as the local sun path; these are combined, however, with the more variable influences of atmospheric conditions such as fog, cloudiness, and the visibility of the sun [Baker *et al.* (ed.) 1993].

This variability makes daylight an interesting, though somewhat unstable source of indoor lighting. In a study on barriers to the exploitation of daylight in building design, for example, Cooper & Crisp [1984] find the variability of daylight's intensity to be an important hinder to designers' deliberate involvement of daylight as a light source in buildings. The same study, however, also shows daylight's variability to be the second most favourable advantage of the use of daylighting in buildings.



[Hopkinson *et al.* 1966:69]

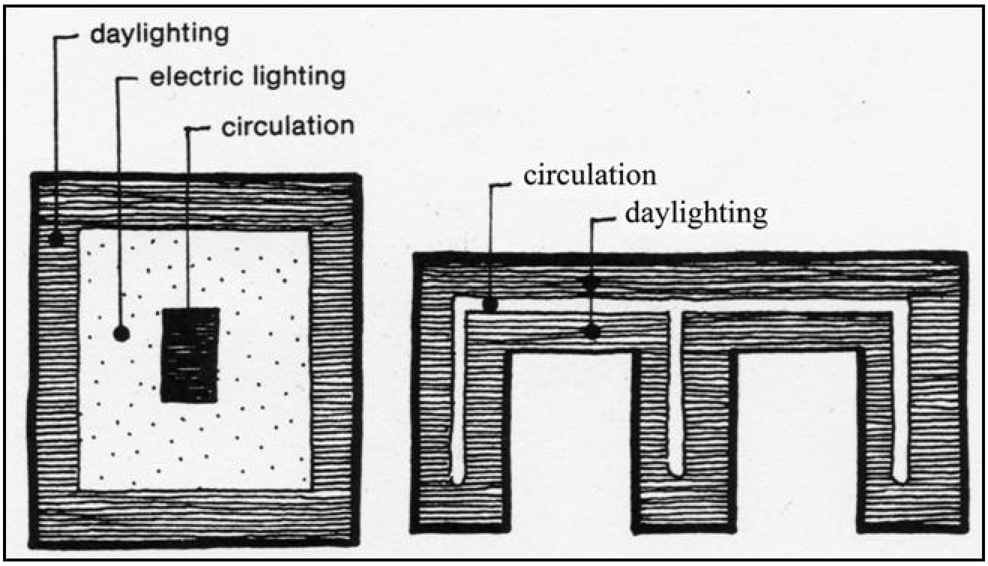
Figure 3-3: *Daylight indoors as a mixture of direct sunlight, diffuse skylight, and their reflection off in- and outdoor surfaces.*

On its path to the indoor environment, the characteristics of daylight as emitted by sun and sky are altered by site topography, vegetation and neighbouring buildings. Objects and surfaces on the site may reduce daylight availability and solar access for a particular building by blocking daylight from entering the indoor environment, or, conversely, reflect additional light indoors (Figure 3-3).

Most elements of the outdoor environment, such as neighbouring buildings, site topography and local climate, are largely out of the control reach of the individual designer. It is, however, possible to control the consequences these elements hold for daylight availability and solar access, by means of:

- The elaboration of **building plan and section**
- The orientation of the various **envelope surfaces**, including daylight apertures, in response to site conditions
- The choice of **ground cover and vegetation** surrounding the building
- The detailed design of **interior finishing, furnishing and fixtures**

Building plan and section determine the amount of indoor surface area that is connected to the building envelope and outdoor environment, and thus allows for daylight apertures; in general, the more compact building plan and section are, the less indoor area can be daylit (Figure 3-4).



From [Moore 1985:63]

Figure 3-4: *The compactness of the building plan and its consequences for daylight access in the indoor environment.*

The *building envelope* itself handles the collection, admission and to a certain extent also distribution of daylight in the indoor environment. Acting as an environmentally selective filter, the envelope ideally allows for daylight to penetrate the indoor environment at the appropriate place and time, and with appropriate properties. This function of the building envelope will be discussed extensively in Chapters 4 and 5.

Having passed through the building envelope, *interior finishings, furnishings and fixtures* further distribute daylight in the indoor environment. Daylight is scattered, diffused and redirected in its reflection off and transmission through the built environment, leading Louis Kahn to depict architectural form and massing as a *daylighting fixture* [Guzowski 2000].

3.2.1.2 The Biophilia hypothesis

Research during the past thirty years reveals a widespread preference for windows in the workplace [e.g., Cakir & Cakir 1998; Küller & Wetterberg 1996; Ne'eman *et al.* 1976]. Not only do windows provide a natural source of light, but, above all, they allow for visual contact with the outdoor environment. This preference for windows has been linked to the assumption that the human brain has an innate need for contact with nature and living organisms, developed in the course of evolution in a natural, *biocentric* environment.

Biophilia, according to the originator of the term Wilson, is *"the innately emotional affiliation of human beings to other living organisms"* [1993:32]. This affiliation is indicated in many research projects, where people are found to prefer a natural view over an artificial (urban) one, particularly related to elements of water and vegetation, with consistent results across individuals, countries and cultures. Furthermore, views containing natural elements provide variation and multisensory stimulation, for example related to the changing of seasons and time of day [Ulrich 1993]. *The Biophilia Hypothesis*, a book edited by Kellert & Wilson [1993], provides an overview of research conducted in this area, and a wide range of authors contributes to an explanatory pattern for this phenomenon.

Not only is a view containing natural elements found preferable; research also suggests this type of view to promote people's physiological and psychological health. Ulrich, having performed long-term research on the health-related responses of natural landscapes on humans, warrants that exposure to nature *"fosters psychological well-being, reduces the stresses of urban living, and promotes physical health"* [1993:73]. Kellert refers to *"a human intuitive recognition or reaching for the ideal in nature: its harmony, symmetry, and order as a model of human experience and behavior [...] feelings of tranquillity, peace of mind, and a related sense of psychological well-being and self-confidence"* [1993:50]. Even indoor plants and posters of nature are assumed to exert a positive influence on people [Heerwagen & Orians 1993].

While there exist ample indications for people's preference for windows and views containing natural elements, researchers are discussing the various factors that might drive this positive response. Is *biophilia* genetically determined, or rather a learnt habit? A natural environment may create the best preconditions for human response, as assimilated during evolution; in modern society, however, a large amount of people grow up in a machine-dominated environment that may suppress this affinity with nature, and only to a variable degree trigger a positive physiological and psychological response [Nabhan & St. Antoine 1993].

In addition, research is needed to study which elements in particular have a positive outcome on people, and whether this effect can be sustained over a longer period of time. For if the effect is genetically determined, and promotes long-term health-related benefits in humans, windows - and daylight - would hold an absolute advantage over artificial lighting in the work environment.

3.2.2 Outcomes of daylighting non-domestic buildings

Architectural form and spatial organisation need to create a precarious balance between functional, aesthetic and financial requirements, daylighting being only one point of interest among many. Daylighting strategies, however, create a sequence of luminous environments that can make a positive contribution to several areas of concern in building design. Three particular aspects are addressed in this section:

- Occupant outcomes
- Energy use
- Financial issues

3.2.2.1 Occupant outcomes

"The criterion of the efficiency of a building lies finally with the assessment by the human occupants" [Hopkinson 1963:vii].

Daylighting strategies supportive of human needs are vital for maintaining a healthy and productive work environment. People adapt physiologically and behaviourally to their environment, and a well-daylit workplace, providing visual contact with the outdoor environment, has been indicated to improve occupant health and well-being significantly. In addition to the *biophilia* effect, daylight as a natural light source has been indicated to exert a profound impact on people's hormones, body temperature, cognitive activities, and mood [Küller & Lindsten 1992; Küller & Wetterberg 1996].

An occupant survey by Cakir & Cakir also suggests that daylight's intensity, spectral composition and spatial and temporal distribution have a favourable effect on human health and well-being in offices. The occupants' self-reported disturbances to health and well-being decrease, for example, with increasing proximity of the workspace to the window; they also decrease in workplaces dominated by daylight, compared to those dominated by artificial lighting. The results of the survey lead the authors to conclude that *"one must assume the existence of environmental conditions with detrimental effects on health at all those workplaces where for certain reasons one is obliged to do without daylight either entirely or partially"* [1998:8-3].

The implementation of daylighting strategies in non-domestic buildings, however, needs to be related carefully to the specific nature of the building program, the occupancy schedule, and the spatial organisation of the tasks and activities to be performed by the building occupants. While daylight and windows in general indeed are found to have beneficial effects, several tasks, such as the use of VDU screens, do not automatically correspond well with daylight. The particular nature and complexity of the tasks should therefore be taken into account meticulously.

In addition, daylighting needs and preferences vary among building occupants, and even for the individual building occupant, according to cultural, functional and individual factors. There exist, for example, large variations in visual capacity between individuals; the number of sensory impaired building occupants has been increasing in recent years, and their needs have to be accounted for [Hill *et al.* 1998]. Hygge & Löfberg [1997] in addition suggest that a building occupant's evaluation of the luminous environment not only depends on the particular lighting conditions, but also on the person's mood and feelings at that time. Research by Begemann *et al.* [1997] further indicates that an occupant's preferred luminous environment is influenced by factors such as sleep quality, sensitivity to light, the synchronisation of the biological clock, and random fluctuations in the occupant's sense of well-being.

A third issue that needs to be considered is *adaptation*. Human visual response is able to adjust to a large part of light's brightness and colour variations in time and space, and may even cover an intensity difference as large as $1 : 10^{14}$, given the appropriate amount of time [Valberg 1998]. Good vision may be obtained within a range of over 1000 to 1, however not when experienced simultaneously. It is therefore necessary to distinguish between the *stimulus*, the actual and physically measurable lighting conditions, and the *sensation*, or the manner in which they are perceived by the individual [Hopkinson 1963].

The human outcomes of daylighting and the luminous conditions that evoke them are further discussed in Section 3.3.

3.2.2.2 Energy use

The effect of daylighting on the energy consumption of a non-domestic building is substantial; appropriate daylighting strategies may provide direct savings related to the reduced use of artificial lighting, and indirect savings due to changes in the thermal load of the building. These savings, however, are not achieved simply by opening up the building envelope and flooding the indoor environment with daylight. The available daylight sources need to be applied effectively.

Despite a tremendous evolution in performance, artificial lighting still consumes a considerable amount of energy; Baker & Steemers [2002], for example, report that 30 to 60 % of the primary energy use in office blocks is due to artificial lighting. Particularly for buildings primarily used during daytime, such consumption of electrical lighting energy appears unnecessary and wasteful.

Daylighting strategies can, to a certain extent, displace the use of artificial light, depending on the particular lighting requirements posed, and the use of adequate control mechanisms that alter the output of artificial lighting in accordance with the availability of daylight and the presence and activities of building occupants.

However, the results of daylight-responsive artificial lighting controls may be rather feeble, according to the *International Energy Agency* (IEA), as *"typical modern office lighting equipment's consumption, even without controls, is less than 10-15 W/m^2. [In addition,] the reduction of light output and energy consumption are not equal: a fully dimmed fluorescent tube may have a light output of 2% of the maximal light flux and will still require 20% of the energy consumption at 100% light output. This is because of the energy consumption of the ballast and the lower efficacy of the dimmed lamp"* [IEA 2001:17,13]. In addition, control electronics and sensors also consume a significant amount of energy.

The thermal load of non-domestic buildings may be influenced by daylighting strategies in three particular manners:

- **Solar heat gain.** Admitting daylight in the indoor environment may cause solar heat gain. Even when the near-infrared component of solar radiation is blocked, daylight is partially absorbed by the glazing of the daylight aperture and by indoor surfaces, released into the indoor environment as long-wave thermal radiation and hence trapped inside the room, as the glass of the aperture is opaque to this type of radiation - the so-called *greenhouse effect* [CIBSE 1999]. While the largest heat gain is created by direct solar radiation, also diffuse radiation may create overload, as it has a wide exposure angle [Lechner 1991]. Non-domestic buildings, even at high latitudes, are generally dominated by cooling load during daytime occupancy hours, and additional solar heat gain is thus ideally avoided by means of proper shading measures.
- **Internal heat gain.** Artificial lighting, electric equipment and building occupants generate heat, which adds to the building's cooling load. As daylight generally has a higher luminous efficacy than many artificial light sources and thus produces less heat per unit of illumination, it can be used to lower the building's cooling load, by means of the appropriate design of daylight apertures, combined with daylight-linked artificial lighting controls.
- **U-value.** A third, more indirect thermal effect of daylighting strategies concerns the U-value of daylight apertures, which tends to be higher than for the rest of the building envelope and thus may cause additional heating load.

Daylight's high luminous efficacy is often mentioned to be an important drive for energy savings when used to offset artificial lighting. Daylight's luminous efficacy, however, is also highly variable; the ratio of luminous to radiant flux depends on solar altitude, cloud cover and water vapour in the atmosphere [Baker *et al.* 1993].

A review by Littlefair [1985] shows that for diffuse radiation, measurements of luminous efficacy vary with solar altitude, mainly ranging from 84 to 173 lm/W. For direct radiation, values are measured roughly between 50 and 120 lm/W for a solar altitude greater than 10^{o} [Baker *et al.* (ed.) 1993]. In addition, daylight's luminous efficacy is strongly modified by the built environment and the daylight aperture.

Hence, the available daylight sources, and the lumens allowed indoors, need to be used effectively [Smith 2004]. Providing the building occupant with a desirable indoor luminous environment while admitting less daylight indoors, would hold large opportunities for energy saving.

3.2.2.3 Financial issues

The use of daylighting strategies in building design is a decision often made based on financial considerations. According to a user study performed by Spectrum Associates [2003] on building designers, owners and developers, the potentially higher investment cost for daylighting is often considered to be more dominating than potential benefits, as the artificial lighting system needs to be installed anyway. The user groups however also mention the ease with which a daylit building can be let, and the good first impression it creates on visitors and clients, which has proven beneficent to business and sales purposes.

In general, daylighting can produce savings in the operational costs of most building programs in terms of energy efficiency, and, potentially, in terms of increased occupant productivity. Research has, as to yet, only provided circumstantial evidence of positive effects of daylight on productivity; however, the subject is being studied intensively, as human cost by far outweighs energy cost in non-domestic buildings.

Several studies show that a highly energy efficient building does not make up for unsatisfied employees. The IEA [2001], for example, reports that annual lighitng electricity consumption in modern offices per person costs barely as much as an employee's wage for 1 hour; a slightly reduced productivity of dissatisfied workers can therefore spoil all expected savings. Similarly, Fontoynont *et al.* [2002] estimate lighting energy savings of 1 to 2 Euros per m^2 per year to be achievable - equal to 1 or 2 hours of salary of an office worker per year for a 10 m^2 work place (Figure 3-5).

Item	Cost per year (€ / yr)	Cost in working hours per year
Office space rental per worker	1500 € / yr	53 hr / yr
Energy (heating, cooling, lighting)	150 € / yr	5.5 hr / yr
Lighting Electricity	30 € / yr	1 hr / yr

From [Fontoynont 2002]

Figure 3-5: *Operating costs of an office work place in € per year, and expressed in hours of staff costs (hypothesis: 1600 hours / year at 29 € / hour).*

The improvement of occupant productivity by means of proper daylighting strategies would thus be a solid economic justification for potentially increased investment costs. Additionally, there is the belief that by creating luminous conditions that match what the occupants want and expect, one can create *positive affect*, a pleasant emotional state that is believed to lead to *"better performance, greater effort, less conflict, and greater willingness to help others"* [Veitch 2000:214]. While a direct link to productivity has not yet been established, daylighting has been documented to positively influence occupant health, comfort and well-being, and increased occupant satisfaction and reduced sick leave indeed contain the promise of leading to a higher productivity level. The lack of evidence of a direct link between daylighting and productivity can partially be ascribed the complexity of lighting-behaviour research, the poor understanding of this domain, and the *"weaknesses in scientific procedure and statistical analysis"* [Veitch 2001b:3].

In the absence of the building occupant, requirements regarding visual comfort may be disregarded in order to minimise the building's energy load. The successfulness of such an approach, however, depends on the amount of people sharing one office, and the frequency and duration of their absence.

The potentially higher investment cost of daylighting devices and controls is, as mentioned earlier, a major issue in daylighting design. Installing high performance daylighting and shading devices and controls may increase initial cost significantly, depending on their commercial availability, their robustness to weather and other damages, and their flexibility. The relevance of such an additional cost depends on a number of factors, such as site and climate conditions, available energy sources, and the desired comfort level. Additional investment costs may be reduced by choosing daylighting systems that can perform multiple functions or replace more traditional building envelope components. Furthermore, they may be compensated by government incentives that promote energy efficiency or the use of renewable energy resources. An increasing availability and interest in daylighting devices and controls is also predicted to lower their investment cost.

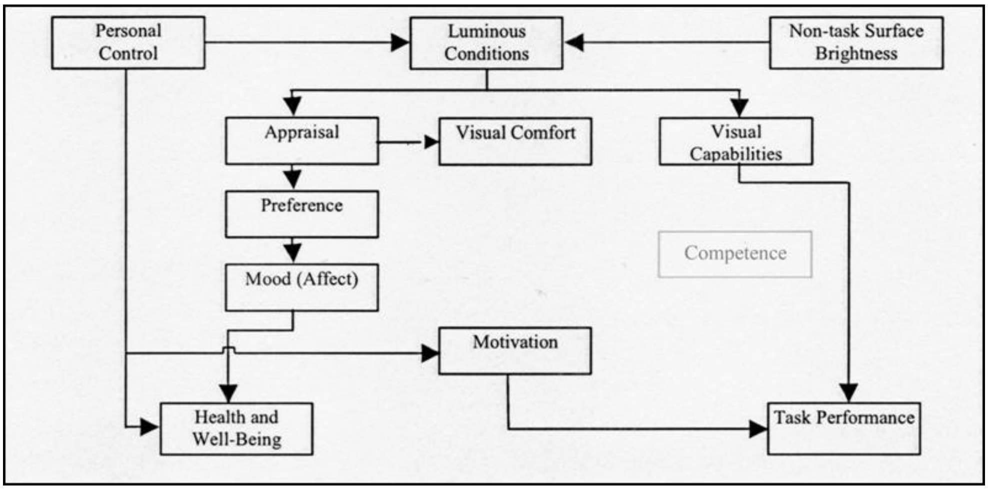
In order to be desirable, increased investment costs also need to be compensated by a decrease in operational costs in a reasonable period of time [IEA 2000]. In addition to offsetting the need for artificial lighting and lowering the building's cooling load, peak energy demands may be reduced, as they tend to coincide with high solar altitude and ample access to daylight. Reduced peak demands, in turn, offer the potential to downsize the HVAC system, and lower energy cost in countries such as Norway that links electricity rates for non-domestic buildings to peak demands.

Successful daylighting strategies, however, do not necessarily require intricate and costly daylighting devices; they depend in the first place on the degree to which architectural form and spatial organisation are adapted to the building's function and to the local site and climate, all of which can be achieved by proper architectural design. According to the IEA [2000], building form and orientation, for example, can reduce energy consumption by 30 to 40 % at no extra cost.

3.3 Daylighting quality in non-domestic buildings

3.3.1 A behavioural definition of daylighting quality

The quality of the daylit indoor environment depends on the manner in which the lighting conditions are perceived by the building occupants during the performance of various tasks and activities. Human requirements for daylight are strongly linked to functional needs, individual and cultural preferences, and regional characteristics with climatic differences. This presents a huge challenge for a generalisation of lighting research results and the development of standard measures. In order to obtain a luminous environment that fulfils human needs regarding health, comfort and well-being in the most energy efficient manner possible, a thorough understanding of the human response to indoor daylighting conditions, along with their spatial and temporal variations, is required.



[Boyce *et al.* 2003:157]

Figure 3-6: *Building occupants' response to their luminous environment consists not only of visual performance, but includes issues of lighting appraisal, room appraisal and personal control as well.*

Research shows that the luminous environment influences building occupants not only by means of illuminance levels and visual performance, but also has significant *non-visual* physiological and psychological effects. A field simulation study by Boyce *et al.* [2003] on lighting quality and office work, for example, shows that lighting appraisal, room appraisal and personal control are important contributors to building occupants' response to the luminous environment (Figure 3-6).

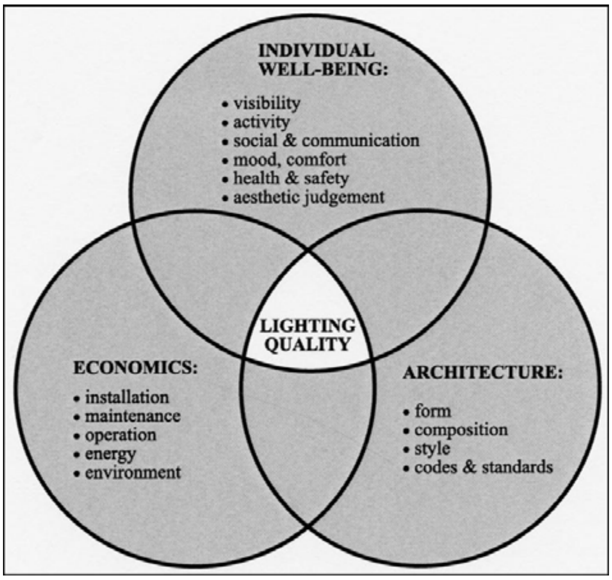
The influence of these conditions is found to be of complex nature, varying according to the human individual, the external environment, and the tasks and activities to be performed. Experts, in addition, do not agree on the significance of each of these conditions, nor on the extent of their interaction.

Veitch & Newsham [1996a] propose a co-ordinated effort to extend the focus of lighting research to incorporate measurements of human perception of and response to the luminous environment, in addition to the primarily technical side of lighting. This approach may, in a long-term perspective, provide quantitative data that can be incorporated into building standards and recommendations. The authors suggest the following definition of *lighting quality* based on environment-behaviour research:

Lighting quality can be defined as *"the degree to which the luminous environment supports the following requirements of the people who will use the space*:

- ***visual performance****;*
- ***post-visual performance*** *(task performance and behavioural effects other than vision);*
- ***social interaction and communication****;*
- ***mood state*** *(happiness, alertness, satisfaction, preference);*
- ***health and safety****;*
- ***aesthetic judgements*** *(assessments of the appearance of the space or the lighting)"* [Veitch & Newsham 1996a:10].

These requirements may also be applied to the quality of a daylit environment [Dubois 2001c; Veitch & Newsham 1996b]. The definition of lighting quality was later expanded to include economic and architectural considerations (Figure 3-7) in balance with human outcomes [Veitch 2001b].



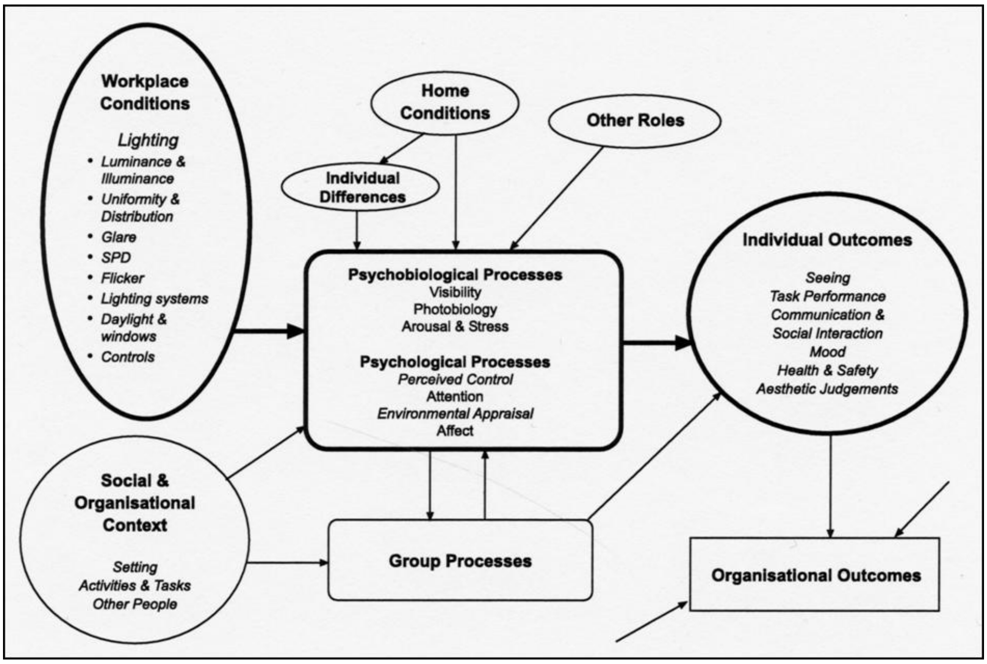
[Veitch 2001b:19]

Figure 3-7: *Lighting quality: the integration of individual well-being, architecture and economics.*

The six human outcomes of (day)lighting quality are now discussed in further detail.

3.3.2 Human outcomes of daylighting quality

The detail of knowledge regarding the six human outcomes of (day)lighting quality identified above varies considerably. The Institute for Research in Construction in Canada provides copious literature reviews on diverse human outcomes of lighting quality (Figure 3-8), such as biopsychological processes (visibility, photobiology and arousal), psychological processes (perceived control, attention, environmental appraisal and affect), and processes that influence productivity (visibility, arousal, stress and positive affect) [Veitch 2000; 2001a; 2001b; Veitch & Newsham 1996b].



[Veitch 2001b:20]

Figure 3-8: *A conceptual model showing relationships between lighting conditions, individual processes, and individual outcomes.*

3.3.2.1 Visual performance

> *"Good lighting quality exists when a lighting system creates good conditions for seeing"* [Veitch & Newsham 1996a:10].

Visual performance is a measure of the speed and accuracy with which a person can perform a visual task in a certain luminous setting. It is measured by means of three factors [Hopkinson *et al.* 1966:6,10]:

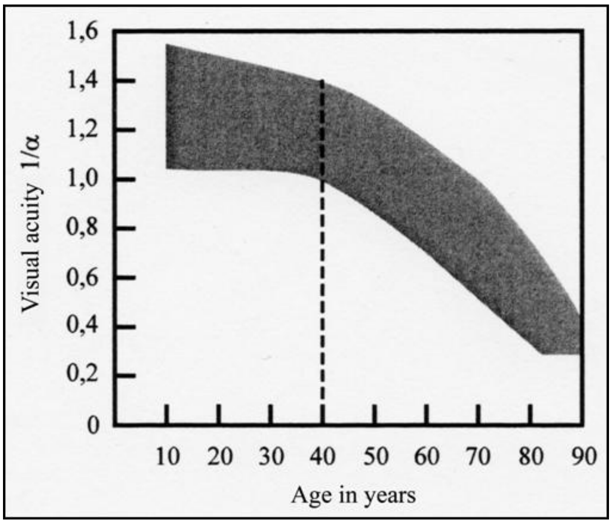
- **Visual acuity**, or *"the ability to distinguish fine detail"*
- **Contrast sensitivity**, or *"the ability to recognize very small contrasts of light, colour and shade"*
- **Task size**, or *"the critical detail of the visual task"*

Visual acuity can be defined as *"the sharpness of vision, measured by the smallest size of detail which can be seen at a given distance"* [Baker *et al.* (ed.) 1993:2.4]. It is a function of the inherent visual acuity of the eye (the optical system, the physical condition of the retina, and the brain's ability to interpret the visual signals), combined with the prevailing lighting conditions, and, particularly, the luminance of the objects that are being viewed [Hopkinson *et al.* 1966].

Contrast sensitivity is the eye's ability to perceive relative differences in luminance or colour. Contrast may occur either simultaneously in adjacent areas of the visual field, or successively in dynamic lighting situations. The higher the contrast, the less contrast sensitivity is needed to perform a given visual task [Baker *et al.* (ed.) 1993; Valberg 1998]. Contrast perception is vital for the human visual response; it enables a person to distinguish between object and background, and to perceive the form of objects. As with visual acuity, contrast sensitivity is a function of the properties of the human eye, combined with object or task luminance [Hopkinson *et al.* 1966].

Task size is related to the critical contrast and the critical size of detail of a visual task, or *"the smallest detail which has to be seen with precision in order to complete the [task] without error [...] expressed either in terms of size of detail and distance from the worker's eye or in terms of the angular subtense"* [Hopkinson *et al.* 1966:10].

Visual acuity and contrast sensitivity decrease with the age of the observer. From a person's late twenties onwards, higher illumination levels, better contrast, and a longer period to adapt to changing light conditions are required (Figure 3-9).



From [Valberg 1998:57]

Figure 3-9: *Visual acuity decreases with the age of the observer, and particularly after having passed the age of 40. α denotes the minutes of arc subtended at the eye. The gray area conveys the variety in published data.*

According to Boyce, the human visual system is able to sustain its performance in a wide range of luminous conditions; however, once a certain boundary of task illumination or brightness distribution is crossed, visual performance decreases quickly [Boyce 1995, in Veitch & Newsham 1996a].

In contemporary workplaces, in addition, an intensification of visual tasks increases stress on the human visual system. Combined with inappropriate lighting conditions such as low illuminance levels or glare, this intensification is prone to cause *visual fatigue* and *asthenopia* or *eyestrain* [Cakir & Cakir 1998].

3.3.2.2 Task performance

> *"Good lighting quality exists when a lighting system supports task performance or setting-appropriate behaviours"* [Veitch & Newsham 1996a:10].

Luminous conditions in the work environment have been found to influence occupant productivity beyond mere visual performance. On the one hand, inappropriate lighting conditions in the work environment may lead to eyestrain, which, sustained over a longer period of time, demands an increased biological effort of the human organism and may give rise to strong fatigue and decreased work performance [Clements-Croome 2000]. A suitable luminous setting, on the other hand, has been indicated to boost worker performance [e.g., Boyce *et al.* 2003].

As mentioned earlier, there is a lot of research activity on the topic of daylight and productivity; clear results, however, have not surfaced yet. While research shows that daylight plays a vital role in the achievement of occupant comfort in most workplaces, in the measurement of human performance, it is difficult to single out and quantify the specific influence of daylight. The relationship between lighting conditions and productivity is influenced by numerous environmental factors, and a straightforward cause-effect explanation does not suffice [Veitch 2000].

One inviting theory is the concept of *arousal*, a general state of mental and physical activation due to sudden strong light stimulation. The wakefulness of the brain is influenced by sensory inputs from its environment, and strong visual stimuli may lead to increased activation [Küller & Wetterberg 1993; Veitch 2001a]. Some researchers have reported increased work performance due to sufficiently high, so-called *biological* illuminance levels [e.g., Brainard & Bernecker 1996; Czeisler *et al.* 1990, in Boyce *et al.* 1997]. But the arousing effect of high illuminance levels may, according to Veitch [2001a], be transitory, and the adaptation mechanism of the human eye needs to be taken into consideration. Studies where an adaptation time of 15 minutes is taken into account, show a much more diffuse relation between increased lighting levels and productivity.

The influence of daylight on task performance, however, reaches beyond mere illuminance levels. A survey among office workers performed by Cakir & Cakir

[1998] shows that a lack of windows in the workplace may induce stress and cause people to feel enclosed, which has a negative impact on work performance. The variation in indoor lighting provided by daylight may be welcomed as an interesting and pleasant feature promoting occupant satisfaction with the work environment. The authors nevertheless warrant that daylighting conditions also may reduce productivity, by severely distracting the building occupant from the task to be performed. In general, the more demanding the task, the less distraction is tolerated from the environment - including the lighting. Highly variable daylighting conditions, or frequently adjusted daylighting devices or artificial lighting levels, will cause stress during the performance of a task that demands deep concentration.

The influence of daylighting on task performance is also tested in various field studies by the Heschong Mahone Group (HMG), in schools [HMG 1999; 2003a] as well as offices [2003b].

A first field study in schools [HMG 1999] compares the performance of students on standard test scores in classrooms with and without windows and daylight. Over 21,000 students and 2000 classrooms in three elementary school districts are investigated. According to HMG, however, only one of the three districts provides sufficiently detailed and extensive data. This district measures the rate of change in test scores over the course of the school year, rather than the absolute student performance or the absolute value of the final scores, thus lowering the influence of other, mainly demographic factors such as ethnicity, economic and social status. In this district, "*controlling for all other influences, we found that students with the most daylighting in their classrooms progressed 20 % faster on math tests and 26 % on reading tests in one year than those with the least. Similarly, students in classrooms with the largest window areas were found to progress 15 % faster in math and 23 % faster in reading than those with the least*" [HMG 1999:2-3]. Also the teachers experience a positive effect of daylight and windows on their task performance. In an interview, one confesses: *"When I've had it with the kids and I can't answer another question, I just take a minute, look out the window at the view, and then I'm OK. I'm calm and ready to go back into the fray"* [HMG 1999:28].

A second study by HMG [2003a], on the effect of windows on student performance in classrooms, does not find similarly positive results for daylighting influences. The results do show an overall positive influence of the higher quality of view on performance, but also a negative effect for factors related to glare, sun penetration and lack of visual control by means of blinds or curtains. It is suggested that HMG that such disturbances created by windows compensate for a potential positive influence of daylight as a natural light source.

HMG [2003b] also conducted a field study on the influence of daylighting and windows on task performance in an office and a call centre, featuring open plan workspaces with cubicles and low partition walls. The results of the study indicate that the quality of the view (in this context, related to the angle and size of the view and its vegetation content) influences task performance. In addition, the occupants' self-reported health conditions, particularly with respect to fatigue, increase with the quality of the view they are exposed to. The glare potential of the windows, on the other hand, is found to have a negative effect on performance.

3.3.2.3 Social interaction and communication

> *"Good lighting quality exists when a lighting system fosters desirable interaction and communication"* [Veitch & Newsham 1996a:10].

Daylight is indicated to affect the social behaviour of building occupants in offices as well as in schools.

Research by Küller & Lindsten [1992], for example, suggests that daylight influences human preferences for individual or group work. The study investigates about 90 school children, age 8-9, in their school environment for a duration of one year; it includes an assessment of cortisol in the children's morning urine, behavioural observations by a trained observer, recordings of annual body growth, and reports of sick leave. The levels of cortisol - a stress hormone and mobiliser of the human organism - mainly follow a circadian rhythm, with typically high levels in the morning, decreasing during the course of the day - possibly with a minor peak late in the afternoon; access to daylight and contact with the outdoor environment exert a significant influence on this rhythm. Küller & Lindsten's results show a strong positive correlation between cortisol levels and the ability to concentrate and co-operate; high levels of cortisol are associated with the inclination for social co-operation, while moderate or low levels of cortisol are linked to individual concentration. These findings warrant that diurnal patterns could fruitfully be included in the planning of work and other activities during the day.

Some studies also indicate that an increase in light levels leads to more and/or louder communication; natural as well as artificial light sources seem to bring about this type of effect [Veitch & Newsham 1996b]. It is suggested that arousal theory accounts for this outcome - higher light levels increase human activation levels, which in turn increase the urge to communicate. As mentioned earlier, however, the human activation system is very complicated, and various factors other than lighting may take part in evoking arousal. According to Veitch [2001a], few studies show clear results; furthermore, they display considerable methodological weaknesses.

3.3.2.4 Mood state

> *"Good lighting quality exists when a lighting system contributes to situationally-appropriate mood"* [Veitch & Newsham 1996a:10].

Access to natural light as well as visual contact with the outdoor environment have been found to influence the mood state of building occupants favourably. As mentioned in Section 3.2.1.2 on *biophilia*, daylight apertures providing a view, and particularly a view including water, vegetation and activity, are reported to reduce stress and contribute to an overall feeling of well-being in humans [Ulrich 1993]. In addition, a view to the outdoor environment enables building occupants to orientate themselves, and prevents feelings of claustrophobia [Bell & Burt 1995].

An office worker survey by Cakir & Cakir [1998] shows that a lack of daylight in office rooms is experienced as stressing by the building occupants. Given a choice, people prefer window areas, even in cases where there is a risk of glare. Negative aspects associated with daylight, such as glare and VDU screen reflections, are reported to be largely outweighed by daylight's positive impact; people show a higher tolerance for discomfort caused by daylight than by artificial light.

The impact of windowless workplaces on human comfort and well-being has been studied by several experts. In general, a lack of windows is found to have a negative influence on the mood state of people. Lack of daylight variation and of a view to the outside makes the work environment seem more monotonous and less complex.

A study by Küller & Wetterberg [1996] investigates the impact of the subterranean, windowless work environment on the health and well-being of male personnel on a military site, working full-time, regular daytime hours in the south of Sweden. The effect of the windowless environment on the chronobiology and sensory stimulation of the personnel is assessed using urine samples for cortisol (a stress hormone) and melatonin (a sleep hormone), the analysis of sleeping patterns, and the personnel's self-reported emotional state and work appraisal, combined with measurements of light, temperature, noise, and air quality. The results indicate that people working in windowless spaces feel tense and claustrophobic and become more negative towards their work; particularly vulnerable are people with sedentary and monotonous work.

3.3.2.5 Health and safety

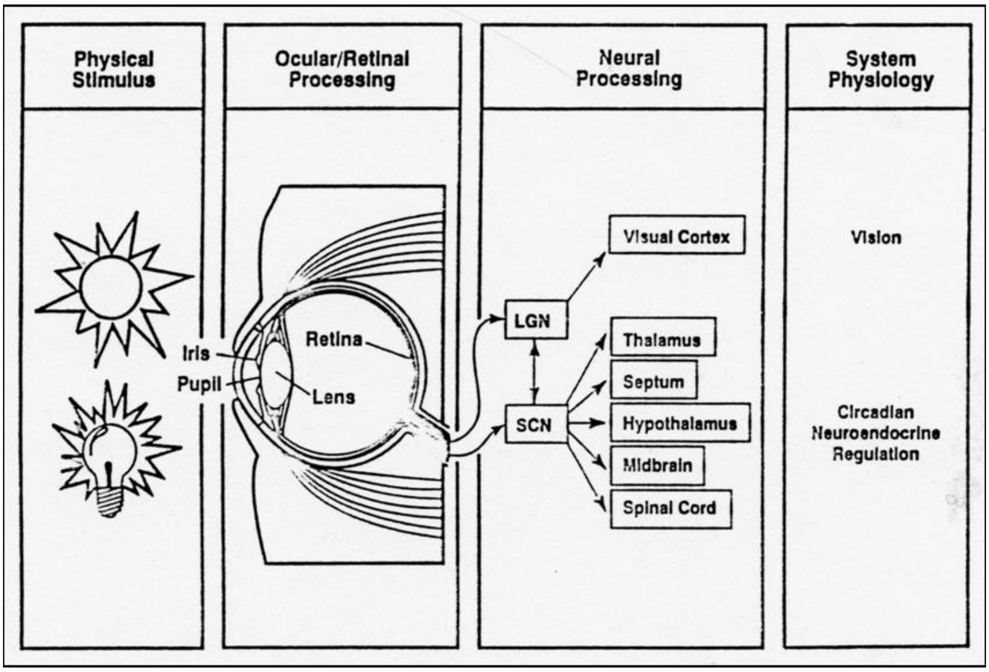
> *"Good lighting quality exists when a lighting system provides good conditions for health and avoids ill-effects"* [Veitch & Newsham 1996a:10].

In the modern work environment, people have come to spend most of their time in artificial lighting, to a certain extent deprived of daylight and a visual connection to the outdoor environment. Simultaneously, they are exposed to artificial lighting whose characteristics have little in common with those of natural light [Veitch 2000].

During the past few years, research has identified visual as well as non-visual effects of (day)light on human health and safety. Intense visual effort due to inappropriate lighting conditions may cause eyestrain, fatigue, headache, irritability, muscular aches, mistakes and accidents. According to Baker *et al.* (ed.) [1993], however, there is no evidence of poor illumination causing organic harm to the human eye. Eye damage can only be caused by over-exposure to light; eyestrain caused by poor lighting, glare, or a difficult visual task is only temporary and disappears along with the conditions that caused it. Yet, as mentioned earlier, eyestrain sustained over a longer period of time may become a stressor for the human organism as a whole, and reduce task performance [Clements-Croome 2000]. A view to the outside world, on the other hand, allows one to change focus from time to time; it helps the eye muscles to relax, offering a visual rest centre in a distant point [Bell & Burt 1995].

Daylight acces at the workplace and visual contact with the outdoor environment also help to synchronise the human *biological clock*, a mechanism that adapts the functioning of the human body to sunlight, with its characteristic spectral distribution and light-and-dark cycle. The human organism displays a typical circadian (roughly 24 hours) rhythm in several forms, such as the regulation of sleep and stress hormones, and body temperature.

Daylight plays a vital role in the entrainment of this clock to a 24-hour cycle; important are the total amount of light, the spectral composition, and the variations occurring during the day and year [Küller & Wetterberg 1996]. This entrainment, however, does not occur by means of the neural pathway responsible for vision, but rather by means of light passing through the retina to other nervous and hormonal centres in the brain (Figure 3-10) [Brainard & Bernecker 1996; Küller *et al.* 1999].



[Brainard & Bernecker 1996:89]

Figure 3-10: *A simplification of the neuroanatomy that mediates the sensory capacity of vision and the nonvisual regulation of circadian and neuroendocrine physiology by light. Each arrow represents a direct monosynaptic connection with the exception of the pathway from the SCN to the spinal cord which requires two synapses. Abbreviations: LGN - lateral geniculate nucleus of the thalamus; SCN - suprachiasmatic nucleus of the hypothalamus.*

A deficit of daylight exposure in the workplace can cause health problems ranging from disturbances of sleep and concentration to depressions [Begemann *et al.* 1997]. Several studies have been performed on the relation between daylight variations and the human biological clock, and more particularly on *Seasonal Affective Disorder*, a form of depression caused by deprivation of daylight. Research by Küller *et al.* [1999], for example, shows that seasonal variations in daylight may cause fatigue, sleep disorder and depressed mood in otherwise healthy people living far north of the equator, such as in England and Sweden. The earlier mentioned study by Küller & Lindsten [1992] on school children in the south of Sweden shows that access to daylight in classrooms affects children's health, behaviour and performance. Work in classrooms without daylight is indicated to influence body growth and sick leave, and to upset the children's basic hormone pattern considerably, leading the authors to suggest that long term use of windowless classrooms be avoided.

3.3.2.6 Aesthetic judgements

> *"Good lighting quality exists when a lighting system contributes to the aesthetic appreciation of the space"* [Veitch & Newsham 1996a:10].

Daylight enhances form, texture and colour. Direct sun provides varying light patterns and dramatic contrasts. Diffuse skylight, on the other hand, softens the appearance of the surroundings. The variations in daylight that occur in time and space can be used to create stimulating architecture and give it a distinct, place-specific character.

Daylighting strategies can range from nearly invisible to becoming a distinctive architectural expression. The appropriate use of daylight in buildings imposes certain requirements on the design of architectural form and massing, the manner in which the building interacts with the local climate and site, and the particular use of finishings, furnishings and fixtures. According to Hopkinson *et al.*, however, *"a timid designer may consider the need for good daylight penetration to be a serious restriction on his freedom of design. Daylight should, however, be looked upon as a means of expression of the skill and artistry of the bold designer"* [1966:431].

3.3.3 Luminous conditions that contribute to daylighting quality

In Section 3.3.1, daylighting quality was defined as *"the degree to which the daylit indoor environment supports the [...] requirements of the people who are using the space"* [Veitch & Newsham 1996a:10]. These requirements range from health and well-being to social interaction, performance and aesthetic judgements. While research has clearly indicated daylight to positively influence human behaviour and preferences, there are currently no exact measurements available to quantify these links. The complex cognitive processes that mediate human response to daylight, the wide variety that appears to exist in individual behaviour and preferences regarding daylight, and poorly defined research make it difficult to obtain quantitative results and generalise them [Veitch & Newsham 1996a; Veitch 2000].

Task illuminance levels have long been identified as a central factor in indoor lighting. Research, however, has shown that a wide variety of luminous conditions are important to human perception of the luminous environment, among which are [Valberg 1998]:

- The intensity and distribution of the light source
- Its variability and spectral composition
- Its interaction with surface texture
- And the human eye's adaptation to successive and simultaneous contrast

In addition, the nature and extent of control given to people over their luminous work environment has shown to exert a considerable influence on their behaviour and preferences regarding daylighting quality.

Several experts have identified lists of luminous and contextual conditions that contribute to good (day)lighting quality, and most of them are fairly similar. Two examples are shown in Figure 3-11.

Veitch & Newsham [1996b]	*Quality of the Visual Environment Committee* (IESNA) [Miller 1994]
Luminance	
Illuminance	Task illuminance
Luminance & illuminance uniformity across tasks	Task contrast
Luminance distribution & illuminance uniformity across rooms	Brightness (comparative luminance) of room surfaces
Glare	Source luminance (glare)
Spectral power distribution / Colour	Colour spectrum and colour rendering
Flicker	
Direct vs. indirect lighting systems	Spatial and visual clarity
Control	Occupant control and system flexibility
Daylighting and windows	Daylight (view) Visual interest Psychological orientation

Figure 3-11: *Two examples of lists of conditions related to the luminous environment that are considered to contribute to good lighting quality.*

There appears to be no agreement in literature, however, on the relative importance of each of these conditions, nor on the manner in which they affect each other.

During the past ten years, several Ph.D. dissertations have also appeared on the topic of daylighting quality, among which:

- **Velds [1999].** Research conducted on *The assessment of lighting quality in office rooms with daylighting systems*, with focus on the following luminous conditions:

  - Discomfort glare
  - Visual performance
  - Task illuminance
  - Uniformity of illuminance
  - Luminance ratios in the observer's central field of view

- **Dubois [2001a;b;c].** Research conducted on *The impact of shading devices on daylight quality in offices*, with focus on the following luminous conditions:

  - Absolute work plane illuminance
  - Illuminance uniformity on the work plane
  - Absolute luminance in the visual field
  - Luminance ratios between work plane, VDT screen and surrounding surfaces

- **Parpairi [1999].** Research conducted on *Daylighting in architecture: quality and user preferences*, with focus on the following luminous conditions:

  - Horizontal illuminance on task surface
  - Vertical illuminance at eye level
  - Luminance levels in the visual field
  - Surface reflectances
  - Illuminance distribution in the room (by means of Daylight Factor on horizontal and vertical plane)
  - Task-to-adjacent, immediate and general surround luminance ratios
  - Vertical-to-horizontal illuminance ratio (directional properties of daylight)

Within the scope of this thesis, six conditions are selected for analysis in the context of an intelligent building envelope. These conditions are chosen because they are considered to incorporate most of the parameters that in research literature are mentioned to contribute to daylighting quality:

- Luminous distribution
- Glare and veiling reflections
- Colour
- Directional properties
- Visual contact
- Individual control

In the following sections, the influence of each of these conditions on daylighting quality, as reported in research literature, is presented. A distinction will be made between the *stimulus*, the actual and physically measurable lighting conditions, and the *sensation*, or the manner in which they are perceived by the building occupant.

3.3.3.1 Luminous distribution

A first type of luminous conditions to influence daylighting quality is the level and distribution of daylight in the indoor environment, brought forth by sun and sky (primary light sources), and by surface geometry and material characteristics (secondary light sources). Objects and surfaces in the indoor environment, unless self-luminous, are only seen by humans because of the light they receive from primary light sources and reflect back onto the human eye [Hopkinson 1963].

The brightness of these objects and surfaces may be described in two manners: their *physical brightness* as measured by a photometer, and their *apparent brightness* as perceived by the human eye.

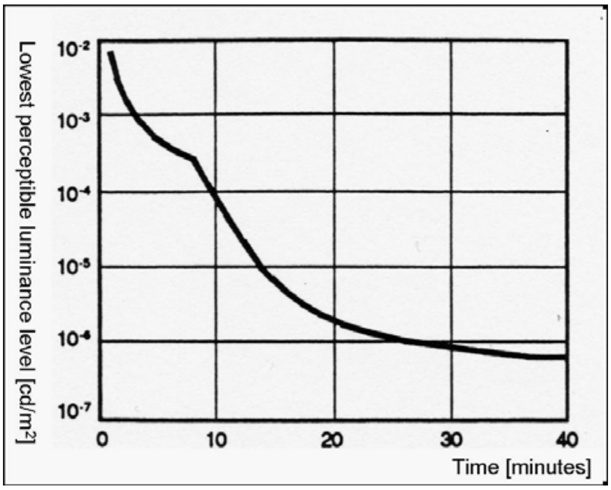
The *luminance*, or physical brightness of an object is the *"quantity of luminous energy propagated in a given direction by a point on a surface"*, measurable by a photometer [Veitch & Newsham 1996b:4]. Surface luminance depends on surface reflection characteristics, combined with the illumination the surface receives from other light sources in the environment. The quantity of visible radiation incident on a particular surface is called *illuminance* [Veitch & Newsham 1996b].

Surface brightness as perceived by the human eye, on the other hand, is brought forth by the luminance of the particular surface, along with the luminance of all other primary and secondary light sources in the field of view. This sensation of brightness is called *apparent brightness* or *subjective brightness*, or often merely as *brightness*. It is different from the physical brightness as measured by a photometer, due to the *adaptation* mechanism of the human eye, which reduces brightness and colour contrasts in the visual field.

Apparent brightness is influenced by the brightness of all of the surfaces in the visual field, such as the reflectance of walls and furniture, and the brightness ratios between the work plane, the VDU screen and surrounding surfaces. The average luminance of all of these surfaces in the visual field is called *adaptation luminance* [Hopkinson *et al.* 1966].

Adaptation of human visual response is important for daylighting quality, as the mechanism helps attenuate the large spatial and temporal variations in brightness and colour that occur in a daylit environment. Daylight's intensity and directionality change continuously throughout the day and create variable luminous patterns in the indoor environment.

The human eye adapts to these changes and alters its sensitivity during the course of time. Optimal adaptation to dark surroundings may take up to an hour, depending on the intensity and duration of the exposure to the previous light conditions (Figure 3-12). Adaptation to brighter surroundings, on the other hand, only takes seconds [Valberg 1998]. When daylight's variations are slow enough for the human eye to adapt to, they become almost unnoticeable. Large or swift variations however, for example under partly clouded skies, may be experienced as very disturbing in the work environment.



From [Lyskultur 1994:10]

Figure 3-12: *The human eye's adaptation to dark surroundings; the lowest perceptible luminance level as a function of time.*

Also the spatial luminance variations that occur across a daylit environment influence the adaptation of human visual response. When a high-luminance light source such as sky or sun appears in the visual field of the occupant, it will have a large impact on the occupant's perception of the room. In the vicinity of the daylight aperture, adaptation luminance will be increased significantly by the presence of sun and sky, causing more remote parts of the room to appear relatively dark and gloomy. For workplaces not located in the vicinity of a daylight aperture, adaptation luminance will be largely determined by the interior finishings and furnishings, causing sun or sky to be perceived as extremely bright when they appear in the occupant's visual field [Hopkinson *et al.* 1966].

When daylight causes a markedly non-uniform luminance distribution across the task area, the human eye needs to adapt to a different brightness level whenever it shifts gaze, also called *transient adaptation*, which causes fatigue and lowers performance [Veitch & Newsham 1996b].

In order to provide optimal luminous conditions for adaptation of the human visual response, experts suggest that luminance ratios in the visual field do not surpass the following values [Baker *et al.* (ed.) 1993; Baker & Steemers 2002; Dubois 2001c; Velds 1999]:

- Between paper task and adjacent VDU 3:1
- Between task and adjacent surroundings 3:1
- Between task and remote surroundings 10:1
- Between light sources and surroundings 20:1
- Between luminaires, windows or skylights and adjacent surfaces 40:1
- Maximum contrast (except if decorative) 40:1
- Highlighting objects for emphasis 50:1

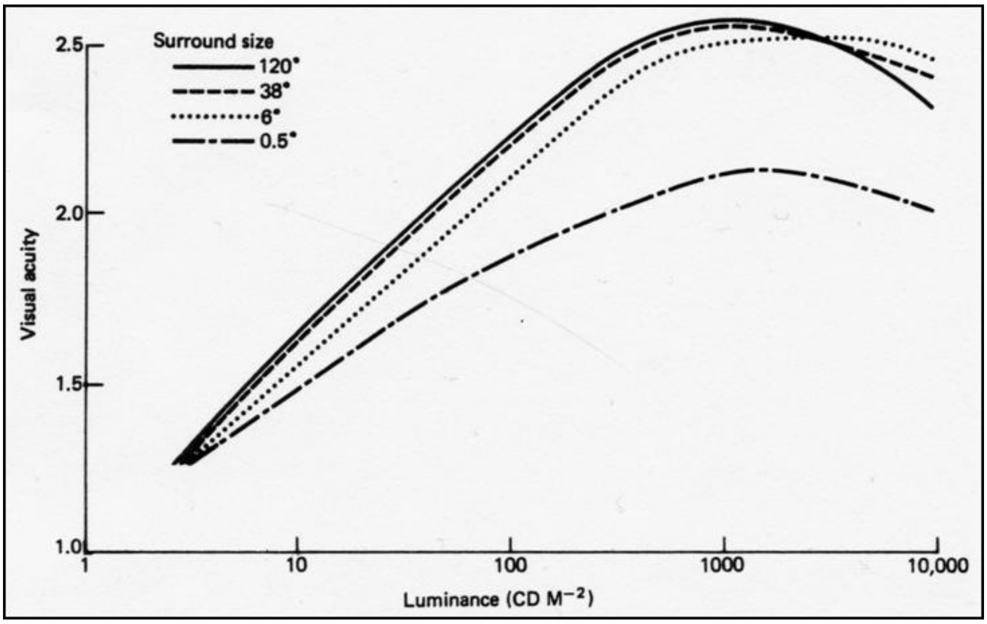
These ratios, however, do not imply uniform or unchanging lighting to be preferable. On the contrary, continuous efforts to maintain a fixed light level may create a monotonous and dull environment, causing the occupant to feel tired and lack attention, while research suggests that a nonuniform luminous distribution increases user satisfaction with the indoor environment [Baker *et al.* (ed.) 1993; Hopkinson *et al.* 1966]. Brightness contrasts, when kept within certain limits, make a room appear more interesting and pleasant; this experience is particularly related to the brightness of vertical surfaces [Tiller & Veitch 1995; Veitch & Newsham 1996b].

What is the optimal level and distribution of daylight in the occupant's work environment? Visual performance is influenced by [Veitch 2001a; Velds 1999]:

- Task luminance levels
- The contrast between task and background
- The type and size of the task
- The age and vision of the observer

Visual acuity and contrast sensitivity increase with increasing task luminance levels, however with diminishing returns (Figure 3-13); once a certain level is reached, visual performance remains quite stable and a considerable increase in task luminance is needed to produce a small improvement in visual performance [Baker *et al.* (ed.) 1993; Valberg 1998]. Increasing illuminance levels will, therefore, improve visual performance, but only up to a certain level. In addition, provided the human eye is given sufficient time to adapt to new illuminance levels, visual performance can be maintained almost independent of illuminance levels [Veitch & Newsham 1996b].

However, a minimum illuminance level is needed to perform a visual task with certain speed and accuracy; too low illuminance levels may cause eyestrain [Baker *et al.* (ed.) 1993]. Küller *et al.* [1999] in addition report that people working in a relatively dark environment are much more affected by winter fatigue than those working in a bright environment. The former group of people is also found to feel more tired, become less active, and socialise less.

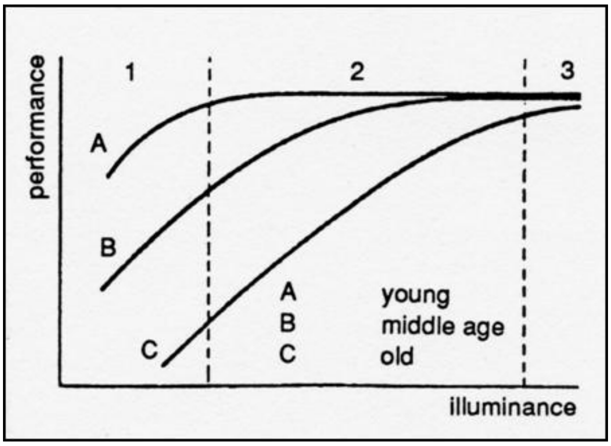


From [Stevens & Foxell 1955, in Boyce 1975:86]

Figure 3-13: *Visual acuity as a function of task luminance; as the luminance of a two-dimensional visual task increases, the size of detail that can be discriminated or recognised decreases. The luminance of the task and surround areas were equal.*

In order to prevent worst practice, recommendations for luminance ratios and minimum illuminance levels are described in national and international building codes and standards for various types of workplaces. In research as well as every-day work environments, however, preferences and needs for daylight illumination are found to display significant inter- and intra-individual variations, according to factors such as the age, vision and mood of the occupant, the type of task or activity, circadian and seasonal variations, and weather conditions.

With increasing age, for example, retinal illuminance declines (Figure 3-14), and, in order to maintain visual performance levels, higher illuminance levels, a larger task size, and better task/background contrast are required [Veitch 2001a]. With regard to inter-individual variations, Begemann *et al.* [1997], for example, report that two subjects participating in a study on lighting preferences, with similar age and background, both show a very distinct preference for illuminance levels - one very high, the other very low - consistent over the course of the year.



[From Boyce 1973, in Baker *et al.* (ed.) 1993:2.5]

Figure 3-14: *Model of general relationship between visual performance and illuminance for three age groups, young, middle age and old. At high levels of illuminance the visual performance of the three groups is very similar. At low illuminances there are very large differences in performance.*

Several field studies also indicate that, when given a choice, a considerable number of people prefers higher task illuminance levels than those needed for visual performance. Begemann *et al.* [1997], for example, report that in a study on lighting preferences, the artificial lighting levels chosen by the subjects are significantly higher than current indoor lighting standards, and suggest these preferences to correspond to lighting levels where biological stimulation occurs. The participants are also reported to prefer a daylight cycle rather than constant illumination levels; a morning, midday and afternoon effect can be distinguished, related to the human circadian rhythm. In addition, lighting preferences appear to depend on weather type and season. Also Vine *et al.* [1998] report that, in a study on office worker response to an automated blind and electric lighting control system, the participants appear to prefer higher daylight as well as electric lighting levels.

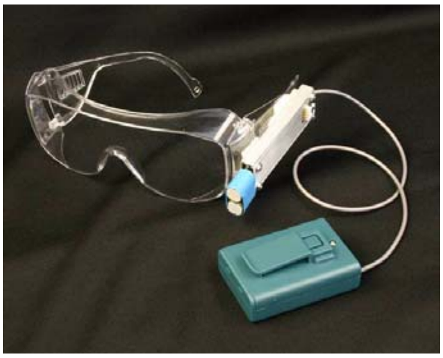
The stimulating effect of bright light in the workplace, assumed to cause *arousal* or physiological and mental activation (Section 3.3.2.5), is also the frequent topic of discussion. The stimulating effect of bright light has indeed been documented and is successfully used to alter people's circadian rhythm in case of sleep disorder, and to lessen depressions caused by Seasonal Affective Disorder. This type of light entrainment, however, with illuminance levels up to 10,000 lx, happens in a controlled environment, and is critically dependent on the timing and intensity of exposure [Holsten & Bjorvatn 1997].In several workplaces, bright artificial light has over a longer period of time been used to counterbalance typical patterns of low performance in early afternoon, at a time when the human circadian rhythm is at a low. This stimulating measure has been reported as successful, but only when introduced at the building occupants' own choice. When introduced against their will, such bright light would be considered a stressor in the work environment, leading to increased stress and lower work performance [Cakir & Cakir 1998].

The wide variation that appears to exist in inter- and intra-individual preferences and needs with regard to the luminous indoor environment warrants that, in order to obtain good lighting quality at the workplace, flexible lighting solutions, combined with a certain extent of occupant control over their own work environment, is recommendable. These variations may, in addition, be used to increase energy efficiency and reduce unwanted solar heat gain. A field assessment in offices by Fontoynont *et al.* [2002] indicates that building occupants often are satisfied with lower ambient light levels when they also have control over the lamp output. The authors thus argue that, instead of focusing on minimum illuminance levels, one may rather aim to follow the specific lighting requirements of the individual occupant in their variations across the time of day, type of acitivity performed, and other relevant factors.

A proper indoor luminous distribution in addition avoids the need for excessively high lighting levels and a corresponding amount of visible radiation admitted indoors. Baker *et al.* (ed.) [1993] suggest that lighting preferences can be met by lower illuminance levels, when combined with an appropriate luminous distribution in the room and task area; instead of providing high illuminance levels, designers should concentrate on parameters such as contrast, uniformity and colour to obtain good comfort.

Increased research focus is also being aimed towards retinal illuminance and its role in the visual perception of the indoor environment as well as circadian regulation of the human body, as circadian regulation may have a different sensitivity for the intensity and spectral distribution of retinal illumination than the visual photoreceptors. Preliminary test results of the study by Ariës *et al.* [2002] also show that retinal illuminance not necessarily proportionally corresponds to horizontal task illuminance nor direct sunlight incident on a facade. Sliney & Marshall [2002] suggest that retinal illumination levels indeed are not directly related to general illumination levels, but rather to the brightness of the light source. In general, it is suggested that an exploration of the effects of retinal illuminance on the visual as well as the circadian system may lead to a quantifiable link between daylight and productivity.

Several research institutes are now performing measurements and field studies in an attempt to quantify the circadian effects of retinal illumination. Among them is the *Lighting Research Center* (LRC) at the Rensselaer Polytechnic Institute in New York, where a *daysimeter*, or headset with incorporated photosensors (Figure 3-15), is developed to quantify the retinal illuminance over time, along with registering the user's head movements and overall activity, and tested in laboratory and field studies [Frering & Leslie 2005].



[Frering & Leslie 2005:7]

Figure 3-15: *A prototype of the daysimeter, designed by the Lighting Research Center to measure retinal illuminance.*

3.3.3.2 Glare and veiling reflections

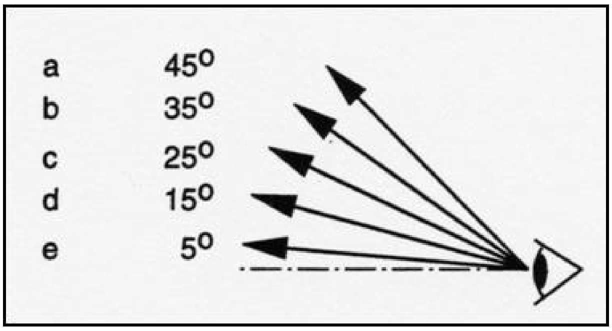
"While high brightness is one of the factors which improve seeing, unwanted high brightness equally can cause a reduction in both visual acuity and contrast sensitivity" [Hopkinson *et al.* 1966:8-9].

Glare, or excessive contrast, is defined by the *Commission Internationale d'Eclairage* (CIE) as *"the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or extreme contrasts"* [CIE 1987]. One can distinguish between *disability glare*, *discomfort glare* and *veiling reflections,* either one of which may occur without the other:

- **Disability glare** is caused by a scattering of light in the eye, which interferes with visual processing, reduces contrast sensitivity and lessens the ability to see detail. Disability glare leads to a reduction in visual performance and may cause eyestrain, but does not necessarily decrease visual comfort. The glare effect is caused by the high intensity, i.e., the amount of light, a light source is emitting in the direction of the eye - be it a small source of high luminance, or a large source of relatively low luminance, such as a view of the sky through a daylight aperture [Hopkinson 1963; Hopkinson *et al.*, 1966].
- **Discomfort glare** is brought about by excessively high brightness (saturation of the visual response mechanism) or uneven brightness (glare by contrast) in the field of view, causing discomfort, distraction, and potentially eyestrain, but not necessarily reducing visual performance [Hopkinson 1963; Hopkinson *et al.*, 1966].
- **Veiling reflections** occur when a light from a bright source (window or light fixture) is reflected onto the task area, reducing contrast between the task and the immediate surroundings [Baker *et al.* (ed.) 1993].

In addition to the factors mentioned above, the *adaptation luminance* plays an important role in the occupant's perception of glare. The level of disability glare as well as discomfort glare increases with a decreasing adaptation luminance; a high background luminance attenuates the glaring effect. When the glare source is large, however, it plays an important role in the adaptation luminance itself, and the attenuating effect of the surrounding surfaces decreases [Hopkinson 1963; Hopkinson *et al.*, 1966]. This attenuation is also found in the earlier mentioned research by Velds [1999].

Also the *position of the glare source in the visual field* influences the occupant's glare experience. The human eye does not accept high brightness levels in the central, foveal visual field, and in this central field the brightness accepted by the eye is thus much lower than in the periphery (Figure 3-16) [Hopkinson *et al.* 1966; Baker *et al.* (ed.) 1993].



[From Robbins 1986:236, in Baker *et al.* (ed.) 1993:2.15]

Figure 3-16: *Acceptable luminance levels as a function of position in the field of vision: (a) 2500 cd/m^2, (b) 1800 cd/m^2, (c) 1250 cd/m^2, (d) 850 cd/m^2, (e) 580 cd/m^2.*

A daylight aperture of high brightness due to sun or sky may cause glare in several manners. Direct sunlight may bother occupants by appearing in their visual field either directly or by reflections off room or task surfaces, thus creating an indirect source of glare. A sky of high luminance or large brightness ratios may have a similar effect; sky luminance can amount to 10,000 cd/m^2 or more if bright sunlit clouds are visible. A bright aperture area may also create a large brightness contrast with the rear half of the room and thus cause the occupants located there to experience discomfort glare. The glaring effect of a daylight aperture can be alleviated by means of contrast grading between the bright aperture and the surrounding surfaces [Hopkinson *et al.* 1966].

Also the temporal luminance variations of daylight influence people's sensitivity for discomfort glare, by means of *transient adaptation*. Frequent variations in the luminance of the glare source cause the adaptation level of the eye to be very unstable, and thus produce a higher degree of discomfort glare than more stable light sources. The adaptation of the eye to changing light levels may take seconds (increasing source luminance) up to one hour (decreasing source luminance), depending on the original source luminance [Valberg 1998]. Short periods of glare are more easily endured than long ones; with an increasing period of exposure, relatively lower luminance levels may cause the occupant to experience discomfort [Hopkinson *et al.* 1966].

The occupants' perception of glare further depends on *task requirements*. People working in static and stressing work environments, demanding a high level of concentration and visual acuity, are more prone to experience glare. Also the type of task to be performed influences glare perception; in particular, people are less tolerant to discomfort glare during the performance of a VDU task than of a horizontal paper task [Velds 1999]. Bright vertical surfaces surrounding the VDU screen may cause transient adaptation; light sources such as vertical windows, that in general would benefit horizontal task visibility, may cause veiling reflections in a vertical and self-luminous VDU screen [Veitch & Newsham 1996b].

Daylight may, however, also alleviate the occupant's experience of glare. Research shows that for mild perceptions of discomfort glare, people are more tolerant towards natural light sources than to comparable artificial light sources, with the same luminance and size [Tokura *et al.* 1996, in Velds 1999]. These findings correspond to research by Cakir & Cakir [1998], who report that, even in VDU workplaces, negative aspects associated with daylight, such as screen reflections, are found to be largely outweighed by daylight's favourable impact on human mood and preferences. People prefer window areas, even when these produce glare, provided the glare remains within limits and relates logically to outdoor weather conditions.

In addition to these factors, a high degree of individual variability can be found in glare experience and the tolerance of particular luminance levels [Veitch 2001a].

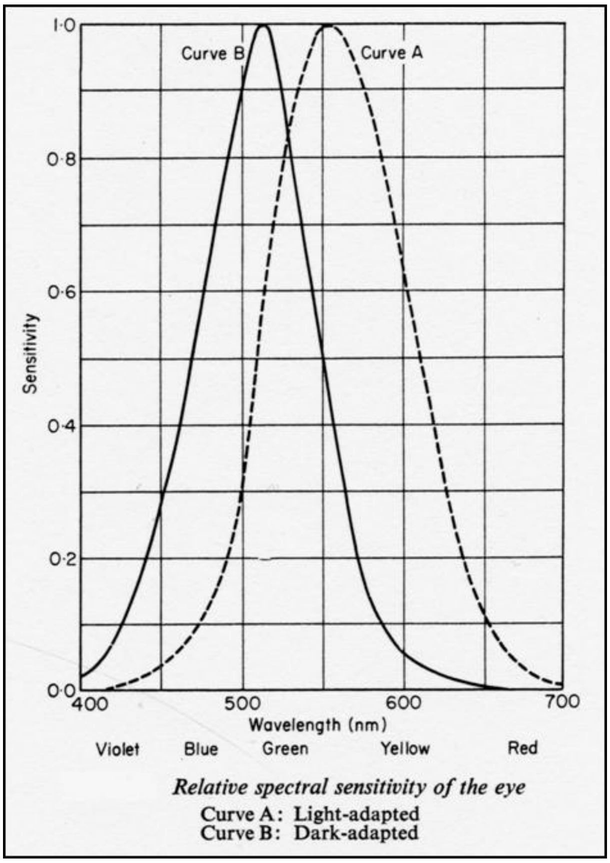
3.3.3.3 Colour

Colour and colour contrast are important elements in the luminous environment. They influence human perception of brightness and allow the eye to distinguish between surfaces of equal luminance. In addition, they affect functions of the human nervous system such as tension, heart rate, respiration, and brain-wave functions [Baker *et al.* (ed.) 1993; Valberg 1998]. Colour perception is also suggested to influence occupants' visual satisfaction with the environment [Chain *et al.* 1999].

Human perception of the colour of a surface is produced by the reflection of visual radiation from the light source illuminating the surface [Lyskultur 1982; Valberg 1998]. The colour of a surface is thus partially determined by its own spectral composition, and, more importantly, by the spectral distribution of the light source. The spectral composition of the light source will also alter the apparent brightness of a coloured surface. Incandescent lighting, for example, with a spectral distribution mainly corresponding to yellow and red tones, will cause yellow surfaces to increase in brightness, while correspondingly decreasing the brightness of blue surfaces [Baker *et al.* (ed.) 1993].

Daylight is a full-spectrum light source with wavelengths between 380 and 780 nm; its spectral distribution varies continuously with atmospheric conditions and the time of day and season. The human eye's sensitivity for daylight depends on the wavelength of the light source and the prevalent adaptation luminance (Figure 3-17). In this respect, one may distinguish between *photopic vision* and *scotopic vision* [Baker *et al.* (ed.) 1993; Berman 1991; Valberg 1998]:

- **Photopic vision** occurs during normal daytime conditions, when the eye is adapted to luminance levels beyond 10 cd/m^2. Fotopic vision causes the human eye to be most sensitive to wavelengths around 555 nm (corresponding to a perceived green-yellow colour), while sensitivity to wavelengths beyond 700 nm (corresponding to red light) and below 400 nm (corresponding to violet light) is very low.
- **Scotopic vision** occurs typically during the night, when the eye is adapted to luminances below 0,005 cd/m^2. It causes the human eye to be most sensitive to wavelengths around 507 nm.
- In between these *pure* types of vision, there is an area of overlap where rods as well as cones are contributing to the occupant's visual experience.

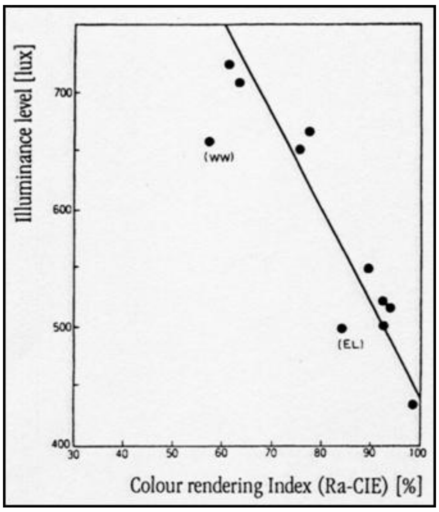


[Hopkinson & Collins 1970:29]

Figure 3-17: *The human eye's spectral sensitivity; (A) photopic vision; (B) scotopic vision.*

Daylight's colour appearance is influenced by the reflections of sky- and sunlight off in- and outdoor surfaces. Diffuse skylight, for example, will cause indoor surfaces to appear more bluish, direct sun produces a more yellowish surface colour, while daylight reflected off earth may produce a rather reddish surface colour [Baker *et al.* (ed.) 1993]. In the indoor environment, however, the light is interreflected between all surfaces, which decreases the influence of the coloured surfaces on the colour appearance of the light. In addition, human visual response is characterised by *colour constancy,* an adaptation mechanism that permits the human eye to distinguish between the spectral characteristics of the light source and the colour of the surface, and neutralises or softens large variations in the colour appearance of light. A white surface, for example, may still appear white even when the spectral composition of the light source changes abruptly, as long as the observer is not given the opportunity to compare the distinct situations [Hopkinson 1963; Valberg 1998].

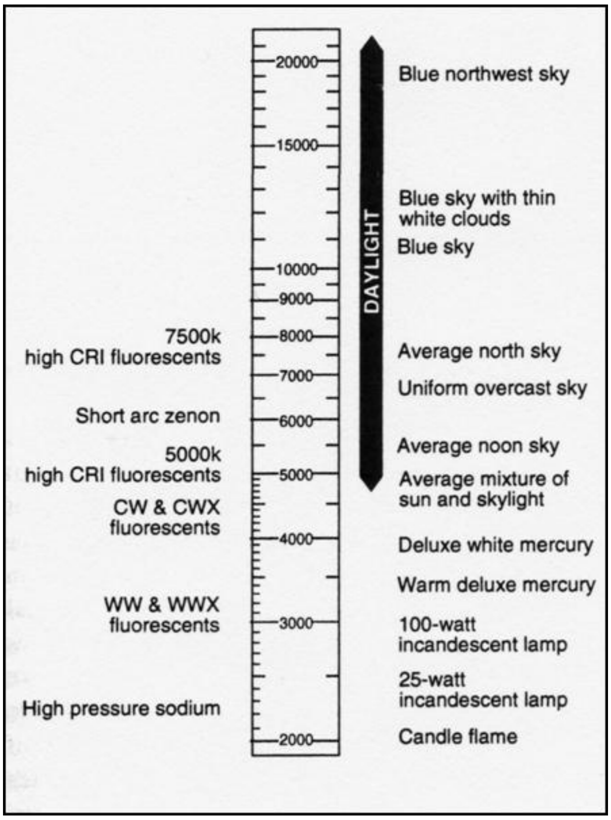
Due to its full-spectrum light, daylight is considered to be the best light source for colour perception. In this respect, a *Colour Rendering Index* (CRI) has been defined that indicates the change in colour perception that will arise by switching from a reference source (typically daylight) to a specific other light source [Valberg 1998]. The Colour Rendering Index is defined by the CIE [1987] as the *"measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation."* Research indicates that light sources with a high CRI (and thus with a spectral composition similar to daylight) increase the apparent brightness of surfaces and thus allow for lower illuminances in the indoor environment (Figure 3-18). Light sources with a CRI of 70, 85 and 100 are found to require respectively 10, 25, and 40 % lower illuminance levels to achieve a particular brightness compared to a light source with CRI 60 [Kanaya *et al.* 1979, in Chain *et al.* 2001].



[Kanaya *et al.* 1979, in Chain *et al.* 2001:194]

Figure 3-18: *The correlation between the CRI of a light source and its accepted luminance.*

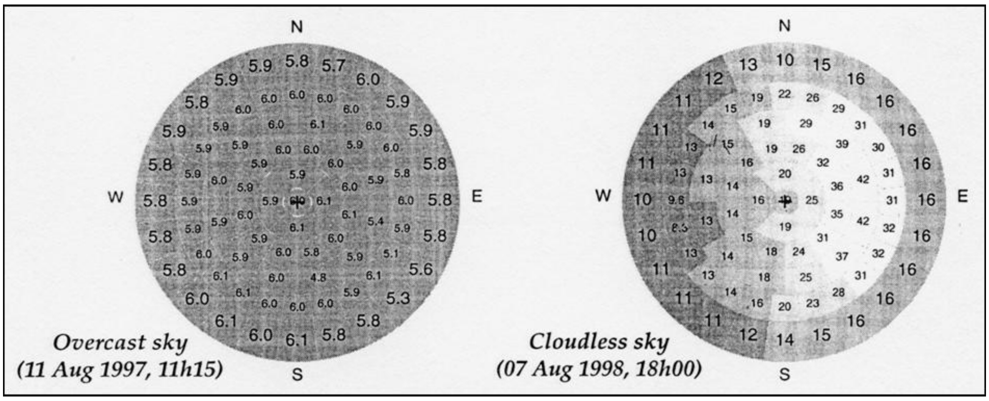
In addition to the CRI, the colour information of a light source is also characterised by its *Correlated Colour Temperature* (CCT), or "*the temperature in degrees Kelvin of a full (black body) radiator which most closely matches the colour of the particular phase of daylight*" [Hopkinson *et al.* 1966:52]. Daylight's CCT displays large variations over time, according to cloud cover and solar position; it may vary from below 3000 K at sunset to 5000-6000 K for overcast skies and beyond 40,000 K for blue sky patches in cloudless skies [Chain *et al.* 1999; 2001]. Figure 3-19 provides an overview of the CCT of different sky conditions and artificial light sources.



[Baker *et al.* (ed.) 1993:2.7]

Figure 3-19: *The Correlated colour temperature (^{o}K) of several electric light and daylight sources.*

The sky vault may, in addition, display a large spatial distribution in CCT. For overcast skies, the CCT is found to be quite uniform, with values around 6000 K; cloudless skies, on the other hand, may display variations in CCT from 7000 K in the solar area to beyond 20,000 K on the opposite side of the sun. It is also suggested that high sky luminance values correspond to low CCT and vice versa (Figure 3-20) [Chain *et al.* 1999; 2001]:



[Chain *et al.* 2001:195]

Figure 3-20: *The measured distribution of CCT in kiloKelvins on sky vault for typical skies.The variation of sky conditions generates a great difference of daylight colour.*

Due to the human eye's adaptation mechanism, not all alterations in CCT are perceived. Measurements performed by Chain *et al.* [1999] show that seemingly white indoor walls with a uniform trend in colour actually display a range of several thousands of Kelvin in variation of CCT. It is additionally commented that the human eye is more sensitive to variations in the CCT range of 3000 to 6000 K than in the range of 10,000 to 20,000 K.

3.3.3.4 Directional properties

Human perception of form and texture in the indoor environment, as well as the overall atmosphere and degree of pleasantness experienced in a room, is greatly influenced by the directional properties of the light sources present. A mixture of directional and diffuse light in the indoor environment generally offers good preconditions for visibility. Light needs to be sufficiently directional in order to create satisfactory modelling effects on three-dimensional objects, surfaces and human faces, and the use of diffuse light alone would lack focus and definition. Directional light, however, also creates strong contrasts and shadows that help to determine the shape and position of objects in the room but may interfere with visibility. Unwanted contrasts need to be softened by adding diffuse light [Baker *et al.* (ed.) 1993; Hopkinson *et al.* 1966].

In a daylit indoor environment, surfaces receive a varying mixture of direct sunlight, diffuse skylight, and their reflections off in- and outdoor surfaces. Direct sun is a concentrated source of light with varying incidence angle; skylight, on the other hand, is a large diffuse source of light with considerable variations in spatial and temporal sky luminance distribution. The admission of daylight to the indoor environment is mediated by daylight apertures, the geometry, position and material characteristics of which exert a significant influence on the particular mixture of sun- and skylight each indoor surface receives, along with room geometry, circadian and seasonal variations in climate, and site conditions. In addition, all surfaces in the in- and outdoor environment act as indirect sources of daylight, and reflect, filter and redistribute daylight. As sun- and skylight have a limited penetration depth in the indoor environment, reflections off indoor surfaces increase in importance as a light source with increasing distance from the daylight aperture.

Direct sunlight may add vitality to an indoor environment; bright sun patches in the room change position and shape according to the cloud cover and the time of day and season. They enliven colour, accentuate texture, and may create dramatic shadows. Direct sun alone may, however, also create harsh shadows, which need to be softened by diffuse skylight and interreflections off indoor surfaces. This diffuse and interreflected light will also contribute to increase indoor daylight levels, and help provide a certain extent of stability in daylight levels and direction with regard to the large temporal variations that may occur in sunlight due to cloud cover. Diffuse and interreflected light alone, on the other hand, create a more restful appearance in the room, but may not provide enough definition of form and texture, which in turn, particularly with relation to visual tasks, may hamper vision and cause visual fatigue [Hopkinson *et al.* 1966].

Though building occupants occasionally appreciate sunlight’s cheerful appearance, direct sun is often undesirable during the performance of specific tasks and activities, particularly when the occupants have no possibility to move or in another way control access to direct sun. Due to its high intensity and variability in position and visibility, direct sun may need to be blocked altogether from entering the indoor environment, or modified to serve as an indirect source of light, by means of techniques such as reflection, refraction and diffusion [Baker *et al.* (ed.) 1993].

3.3.3.5 Visual contact

Visual contact with the outdoor environment is related to the degree of connection or separation the building occupant experiences between the interior and exterior of the building. It involves a view from in- to outside along with the perception of privacy or shielding options from passers-by and neighbouring buildings.

Research during the last thirty years reveals a widespread preference for windows in the workplace. Most highly regarded is a view to the outdoor environment, second highest ranks daylight as a source of light. A survey performed by Ne’eman *et al.* [1976] on housing, schools, office buildings and hospitals indicates that the majority of building occupants prefers a congenial view - trees and grass being the most popular - over other amenities related to indoor daylighting. Research by Cakir & Cakir [1998] suggests that most office workers prefer a work area in the vicinity of a window, in order to have a view out; this preference is upheld even when they frequently perform VDU tasks and there is a risk of glare. Views to the outdoor environment preferably contain one or more elements of interest, such as nature or changing activities. In addition, views are preferred to include both the ground outside and some skyline [Bell & Burt 1995].

These results may be related to the *biophilia hypothesis*, a topic discussed earlier in Section 3.2.1.2. Visual contact with the outdoor environment provides building occupants with a spatial and temporal reference. A view helps people to keep in touch with the changing weather conditions and time of day, allows people to orientate themselves in the building, and may even prevent claustrophobic feelings. In addition, research suggests that visual contact with the outdoor environment makes building occupants more tolerant towards variations in indoor climate, provided they remain within certain limits and relate logically to outdoor conditions [Cakir & Cakir 1998].

A view to the outdoor environment is also reported to improve work performance. It allows the eye to rest on a relatively distant point, and thus relaxes the eye muscles. In addition, views containing nature have been reported to reduce stressful thoughts, hold interest, and elicit positive feelings [Ulrich 1993]. Lack of exposure to natural light and a view to the outdoor environment, on the other hand, has been reported to exert a negative impact on human well being and performance. It may increase stress and cause people to feel enclosed [Cakir & Cakir 1998].

Building occupants often do not accept daylight without a view; daylight apertures that provide a restricted or distorted view tend to be resented, except in circulation spaces where people do not have to spend a large amount of time [Bell & Burt 1995; Littlefair 1996]. Studies of windowless environments by Küller *et al.* [1996] suggest that a lack of windows makes the indoor environment seem more monotonous; people feel more tense and claustrophobic, and develop negative thoughts about their work. Another study by Küller *et al.* [1999] shows people sitting within two meters from a window to be more sociable and have higher activity levels than those people sitting further away from the window.

Contact with the outdoor environment is also related to the degree of privacy a building occupant perceives; at particular times, the occupant may feel as if on display, and the possibility to shield herself from the outdoor environment may be just as important as having a view. The occupant’s perception of privacy with regard to the outdoor environment may be influenced by the presence and activities of people outdoors and in neighbouring buildings.

3.3.3.6 Individual control

In addition to the five contributors mentioned earlier, the occupants' perception of control over their luminous environment is found to be of vital importance for indoor daylighting quality. *Control* in this context may be defined as *"the perceived ability to significantly alter events"* [Burger 1989:246]

The range in nature and degree of control given to building occupants over their work environment was already discussed in Chapter 2 in relation to the design and operation of an intelligent building envelope. This topic is also highly relevant in the context of daylighting quality, as daylighting needs and preferences are reported to vary for each individual building occupant and among building occupants due to functional, cultural, meteorological and individual factors. Individual control options may consist of simple measures such as opening a window, using Venetian blinds, or changing the position of the workplace in response to direct sun.

In addition, it is warranted that any system attempting to control indoor daylighting quality, in order to be successful, needs to be able to comply with individual needs. In a study on blind control and artificial lighting control systems, Velds [1999] reports that the most important complaint from the subjects is the inability to overrule the system, leading the author to conclude that the user should have the opportunity to overrule both the blinds and the artificial lighting control system. Research by Cakir & Cakir [1998] shows that, when given a choice, people prefer a lighting set-up that combines ambient lighting with task lighting; the authors suggest that this preference is most likely due to the degree of individual control task lighting offers the subjects over their own luminous environment, as opposed to all the other, non-controllable lighting set-ups that are presented.

User studies by Heerwagen & Diamond [1992] indicate that building occupants prefer to control their luminous environment themselves, rather than having a control system decide. In correspondence with the discussion presented in Chapter 2, however, the authors warrant that control may become a negative experience when the occupants need to exert it too often, or the controls are too complicated in use and thus create a fear of failure. An additional impact is the creation of a phenomenon the authors call *desk potato*, where occupants, with the controls too close at hand, no longer have to move from their desk in order to adjust their (luminous) work environment, which may have considerable negative effects on occupant physiology as well as social atmosphere at the workplace.

4 Functional analysis: envelope intelligence for daylighting quality

4.1 Requirements for adaptation in daylighting

An intelligent building envelope ideally is able to adapt to its environment, to cope with conflict and variability, and to handle occupant behaviour in a suitable manner. How may such intelligence fruitfully be applied in the context of daylighting quality?

There exists a wide range of technologies that may be implemented in an intelligent building envelope, enhancing the envelope's ability to perceive, reason and act. This, however, does not automatically benefit daylighting quality. As discussed in Chapter 3, indoor daylighting quality is inherently dependent on the manner in which the building occupants experience their luminous environment, an experience which is influenced by the adaptation of human visual response to brightness and colour, and by a large variation among and within individuals. Daylight's variations are in some circumstances appreciated, in others preferably mitigated.

Thus, the influence an intelligent building envelope exerts on the collection, admission and distribution of daylight indoors, needs to be based on human requirements, and not on what is technically possible. Consequently, one may ask:

> What kind of building envelope intelligence is desired in the context of daylighting quality?

Chapter 4 consists of an analysis of functions an intelligent building envelope may perform in order to improve indoor daylighting quality, in particular with regard to the following luminous and contextual conditions:

- Luminous distribution
- Glare and veiling reflections
- Colour
- Directional properties
- Visual contact with the outdoor environment
- Individual control

These conditions are brought forth by a number of environmental factors related to climate, the built environment and the building occupant, subject to variations an intelligent building envelope has no control over.

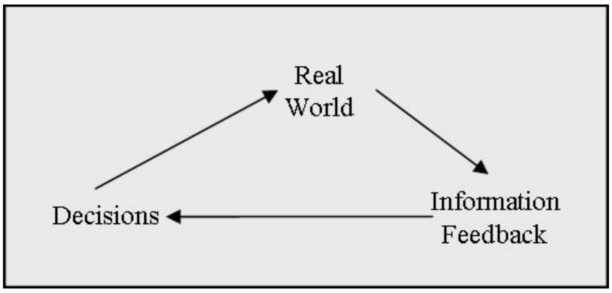
The consequences of these conditions on indoor daylighting quality, however, can be controlled and optimised by the building envelope, by means of perception, reasoning and action processes (Figure 4-1).

Perception	• The indoor luminous environment • The outdoor environment • The building occupant • The building envelope's own performance
Reasoning	• Assessment of the perceived conditions • Elaboration of an appropriate strategy • Prediction of the development of environmental conditions • Learning of the occupant's individual needs and preferences • Training of the envelope's memory
Action	• Execution of the chosen strategies • Communication with the building occupant • Feedback on the successfulness of the chosen strategies • Update of the envelope's memory

Figure 4-1: *A list of functions an intelligent building envelope may be expected to perform in order to control the impact of the environment on indoor daylighting quality.*

The extent to which all of these functions need to be performed, however, depends on the particular environment, and on the resources the building envelope has at its disposal. As mentioned in Chapter 2, the response of an intelligent building envelope to its environment may consist of a simple *reflex action*, a *"simple response that follows on directly and inevitably from the stimulus"* [Beukers & van Hinte 1998:45], or, on the other hand, be characterised by long circuits, involving the use of mental models [Oléron 1969]. This variation in response modes of the envelope towards its environment, is described in Figure 4-3 by means of process called "*double-loop learning*" [Argyris 1985, in Sterman 2000].

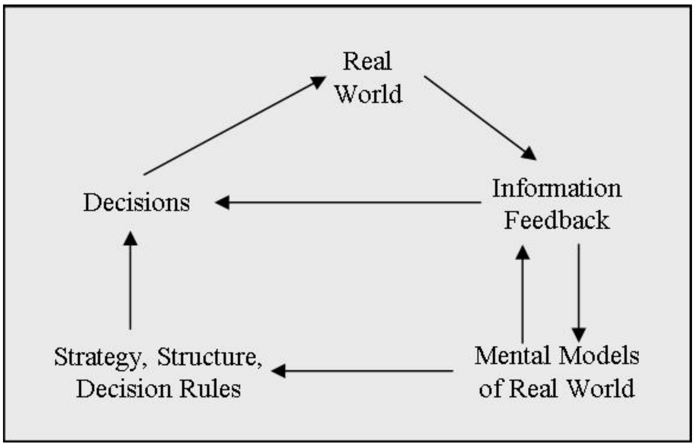
In the short loop (Figure 4-2), information regarding the state of the outdoor environment influences the system's (or, in this case, envelope's) decisions and actions, which, in turn, exert an impact on the state of the outdoor environment.



From [Sterman 2000:15]

Figure 4-2: *Single-loop learning, where feedback from the real world influences the system's decision-making.*

In the long loop (Figure 4-3), the information received from the outdoor environment is stored in the system's (envelope's) memory, which is continuously updated in interaction with the environment, from where it influences the system's long-term strategies.



From [Sterman 2000:19]

Figure 4-3: *Double-loop learning, where information from the real world in addition is used to update the system's memory and influence long-term strategies.*

Figure 4-4 shows how this double-loop learning may be connected to the context of an intelligent building envelope and its processes of perception, reasoning and action.

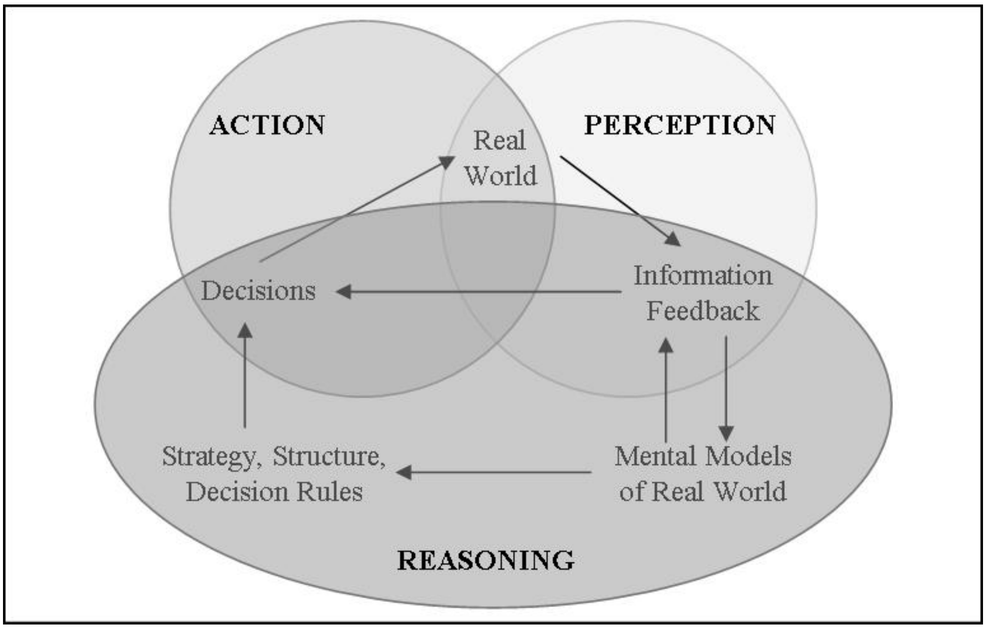


Figure 4-4: *Double-loop learning in the context of an intelligent building envelope and its processes of perception, reasoning and action.*

In Chapter 4, it is examined in which manner an intelligent building envelope, by means of all of the functions depicted above, can partake in the creation of six types of luminous and contextual conditions supportive of good indoor daylighting quality. The envelope functions are analysed in three main groups, according to levels of service that may be provided by an intelligent building envelope:

- The correction of unsatisfactory conditions
- The prevention of unsatisfactory conditions
- The provision of optimised (customised) conditions

Within each of these levels, it is analysed how an intelligent building envelope, by means of its perception, reasoning and action processes, is able to contribute to good indoor daylighting quality.

While each of those six conditions is analysed separately in Chapter 4, in reality, they are not distinct items, but are entangled and may even conflict with each other. These conflicts, however, will become apparent in Chapter 5, featuring an evaluation of physical examples that are performing one or several of the functions discussed in Chapter 4, and assessing the consequence pattern they generate.

4.2 Luminous distribution

	Correction	Prevention	Customisation
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

An intelligent building envelope ideally is able to create a luminous distribution in the indoor environment that corresponds to the individual occupant's needs and preferences. The envelope's influence on the indoor distribution of daylight may take on several forms:

- To correct the luminous distribution at the occupant's request
- To prevent the occurrence of an unsatisfactory luminous distribution
- To customise the luminous distribution to the occupant's preferences

4.2.1 Correction of unsatisfactory luminous distribution

A basic level of service the building envelope may provide, is to correct the distribution of daylight in the indoor environment at the request of the building occupant. The successfulness of this approach depends, on the one hand, on how well the occupant manages to clearly describe the problem experienced, and, on the other hand, on how well the envelope understands the request forwarded by the occupant: which conditions are experienced as unsatisfactory, and why? The occupant may be dissatisfied with the current luminous distribution, as well as with the manner in which it is handled by the envelope. Functional criteria related to the envelope's ability to correctan unsatisfactory luminous distribution are listed in Figure 4-5.

Correction	Prevention	Customisation
• Location of perceptory system • Flexibility of perceptory system • Evaluation of response strategies • Interpretation of user requests • Response time • Execution of chosen strategy • Correction of illuminance levels • Correction of brightness ratios		

Figure 4-5: *Functional criteria related to the envelope's ability to correct an unsatisfactory luminous distribution.*

• **Location of perceptory system.** In order to assess the nature and degree of correction needed to respond to the occupant's request, the envelope first needs to identify the current situation. Physical stimuli such as task illuminance levels and luminance ratios in the occupant's visual field, around the task surface and across the room, may be monitored by the envelope directly in the indoor environment, in the occupant's visual field. Alternatively, these parameters may be deducted from outdoor measurements, for example by means of measuring the incidence of solar radiation on the envelope surface, calculating the corresponding luminous intensity and directionality, and therefrom deducting luminance and illuminance levels for specific indoor surfaces.

• **Flexibility of perceptory system.** The choice of perception strategy strongly influences the flexibility with which measurements can be taken. The registration of luminance and illuminance levels in the occupant's visual field needs to be related to the occupant's position in the room, the view angle, and the type of task performed. Indoor measurements of luminance and illuminance levels may have limited flexibility due to the position or opening angle of the sensing equipment. Outdoor measurements, on the other hand, demand a fair amount of calculation along with detailed knowledge of envelope and indoor surfaces' geometry and material characteristics, in addition to furnishings, fixtures and fittings. They do, however, require for only a fixed amount of parameters to be measured. In- and outdoor measurements may also be combined in order to obtain more complete and detailed information.

• **Evaluation of response strategies.** Having received the occupant's requirements for change, an intelligent building envelope needs to assess how to adjust its morphology and alter the daylight distribution in the indoor environment:

- Which adjustments are relevant?
- Which adjustments require the least amount of resources?
- Which adjustments provide the smoothest transition?
- Are the side effects, on factors such as glare, view and energy use, acceptable?

• **Interpretation of user requests.** While all of these effects may be assessed, the chance exists that the occupant is not satisfied with the changes, as the envelope is able to work with the physical stimulus but not with the manner in which it is sensed by the building occupant. In *correction mode*, the envelope's function is simply to provide the changes requested by the occupant (e.g., higher task illuminance), even though there might be better fit alternative solutions (e.g., to optimise brightness contrasts around task surface).

• **Response time.** In addition, the response time of the envelope to the occupant's request is of the utmost importance. Daylight is a variable light source, and the envelope's adjustment may have become irrelevant by the time it is executed, potentially increasing the occupant's dissatisfaction.

• **Execution of chosen strategy.** By adjusting the morphology of its daylight apertures, an intelligent building envelope is able to control the distribution of daylight in the indoor environment, and alter illuminance levels and luminance ratios according to the occupant's request.

• **Correction of illuminance levels.** Illuminance levels on a task surface may be increased by means of direct or indirect illumination. The envelope can adjust the morphology of its apertures in order to allow more light to pass through its daylight apertures and reach the task surface as direct illumination with an appropriate incidence angle. This option, however, becomes less achievable with increasing distance between the daylight aperture and the task surface. In addition, the envelope may increase the amount of indirect illumination by having incoming daylight reflect off highly-reflective envelope and indoor surfaces, and redirect it to the task surface.

• **Correction of brightness ratios.** In order to increase the overall brightness of the room, daylight may be guided to the ceiling and upper wall area, from where it is further reflected into the room; also other highly-reflective surfaces adjacent to the aperture may be used to achieve this effect. Simultaneously, the building envelope needs to keep the luminance ratios in the occupant's visual field within acceptable limits in order to avoid transient adaptation and gloominess. The penetration depth of daylight can be increased by augmenting the head height of the apertures or by moving them upwards. Also fixtures and furnishings may be used to reflect and redirect light; however, care should be taken that they not give rise to disturbing shadows. If building plan and section allow it, an intelligent building envelope can, in addition, utilise daylight apertures in distinct room surfaces to have light arriving from different angles and even out daylight distribution in the room.

4.2.2 Prevention of unsatisfactory luminous distribution

In addition to reacting to occupant requests, an intelligent building envelope may, if desired, also take proactive measures to prevent an inappropriate luminous distribution from arising in the indoor environment. To this purpose, the envelope needs to be able to predict the development of weather conditions, and link them to the presumed needs of the building occupants. Functional criteria related to the envelope's ability to prevent an unsatisfactory luminous distribution are listed in Figure 4-6.

Correction	**Prevention**	Customisation
	• Prediction of environmental conditions • Prediction of occupant needs • Application of standard sky models • Application of standard lighting recommendations • Interpretation of human visual response • Interpretation of anticipated environmental conditions • Evaluation of response strategies	

Figure 4-6: *Functional criteria related to the envelope's ability to prevent an unsatisfactory luminous distribution.*

• **Prediction of environmental conditions.** Avoiding an inappropriate distribution of daylight indoors, requires for an intelligent building envelope to be able to predict the development of potentially disturbing conditions in the outdoor and indoor environment. Of particular importance are the stability of the sky luminance distribution - which depends on the nature, speed and direction of the cloud cover - and the correspondent visibility of the sun, as these originate all other (secondary) sources of daylight, and cause most variations to occur.

- **Prediction of occupant needs.** In addition, the envelope needs to predict when the distribution of daylight in the indoor environment will be experienced as inappropriate by the building occupant. The envelope, however, can register and interpret a selection of physical stimuli, but is not able to measure the occupant's sensation directly. Particularly challenging is the brightness adaptation of the human visual response, causing the apparent brightness of a surface to be influenced by the luminance of all of the surfaces in the occupant's visual field.

- **Application of standard sky models.** The monitoring of spatial and temporal variations in atmospheric conditions in real-time may be combined with standard sky models to predict local variations in sky luminance distribution and foresee the occurrence of disturbing events. The *Commission Internationale de l'Eclairage* (CIE) has elaborated various standard sky models based on measurements of typical cloud distribution patterns, which may be combined to characterise the typical daylight availability at a certain site. This information then needs to be updated for the influence of objects and surfaces on the site, which may block sky- and sunlight from particular angles, but, on the other hand, also may reflect light indoors from sky areas otherwise inaccessible for a particular envelope orientation.

- **Application of standard lighting recommendations.** In order to relate these predictions to the occupant's sensation of disturbances in indoor luminous distribution, the building envelope may compare the anticipated illuminance levels and brightness ratios to standard lighting recommendations, stored in its memory. The use of such recommendations, however, presents two main challenges: inter- and intra-individual variations, and the adaptation of the human visual response.

- **Interpretation of human visual response.** A first challenge is the average user represented in the building standards and lighting recommendations. As discussed in Chapter 3, the needs and preferences of the individual occupant may vary according to factors such as vision, mood, time of day, weather conditions, and type of activity. A building occupant may be satisfied with the luminous distribution even though it does not comply with building standards and recommendations, and vice versa. The adaptation process of the human eye, in addition, alters its sensitivity and tolerance for luminance and illuminance levels compared to what may be expected from the absolute values. Given the appropriate amount of time, adaptation may cause the human eye to have a higher tolerance for excessively high or low levels of brightness than a measuring device would indicate. Large spatial or temporal variations in brightness, on the other hand, may cause the building occupant to perceive the luminous environment as unsatisfactory even though the absolute values would be acceptable.

• **Interpretation of anticipated environmental conditions.** Predicting the occurrence of potentially disturbing conditions gives the envelope the opportunity to attenuate the impact of these conditions on the occupant's luminous environment. Knowing approximately which time scale to take into account when reacting to variations, enables an intelligent building envelope to smoothen the transition from one set of conditions to another. Highly variable sources are preferably avoided since they may require more intense supervision and more frequent alterations in envelope morphology. If necessary, the envelope can choose other daylight sources that are less prone to cause an inappropriate luminous distribution.

• **Evaluation of response strategies.** The stability of daylight sources is an important criterion in the choice of strategy the envelope makes. When the envelope perceives or predicts disturbing conditions of a transient nature, it needs to assess whether the adjustments in its morphology in fact would not prove to be more disturbing to the occupant than would the temporarily unsatisfactory conditions. The disturbances may be of a transient nature due to, for example, highly variable weather conditions, causing the disturbance to occur for only a few seconds; in addition, their effect may wear off, given the appropriate amount of time, due to the adaptation mechanism of the human eye. Alternatively, the building envelope may choose to take on an intermediate posture that perhaps does not offer maximum protection from the disturbances, but does attenuate them and the corresponding discomfort for the building occupant, and offers the advantage of not requiring adjustments as frequently and as extensive, thereby reducing the chance of in fact creating a new source of disturbance to the building occupant. When the disturbing conditions may be assumed to be long-term, on the other hand, the envelope can adapt more quickly and more precisely to the correspondent conditions.

4.2.3 Customisation of luminous distribution

The performance of an intelligent building envelope may be expanded to include learning and memorising occupant needs and preferences related to diverse environmental conditions, in order to optimise daylight's distribution in the indoor environment to the individual occupant. Functional criteria related to the envelope's ability to customise the indoor luminous distribution are listed in Figure 4-7.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Memorisation of occupant preferences • Customisation of luminous distribution

Figure 4-7: *Functional criteria related to the envelope's ability to customise the indoor luminous distribution.*

- **Interpretation of occupant requests.** In order to learn how the individual occupant's needs and preferences deviate from standard recommendations, an intelligent building envelope can register the occupant's requests regarding luminous conditions as well as the manner in which the envelope controls them, and relate them to the context in which these requests are made, such as weather conditions, the time of day, and the type of task performed; also the age and vision of the occupant can be taken into account.

- **Memorisation of occupant preferences.** The registered occupant preferences may be compared to and used to update the standard lighting recommendations stored in the envelope's memory, if the new values prove to be more fit for the individual occupant. The envelope may also attempt to learn the nature and frequency of adjustments in envelope morphology tolerated by the occupant, by means of direct occupant feedback as well as by interpreting of the occupant's behaviour; an occupant constantly attempting to adjust the luminous distribution does probably not approve of the envelope's strategies.

- **Customisation of luminous distribution.** Based on the occupant's individual preferences and needs, an intelligent building envelope can determine the amount of daylight to be directed to each room surface, and select daylight sources with a suitable luminance distribution, stability and accessibility in order to accomplish the appropriate daylight levels and distribution indoors. The predicted luminance distribution and stability of the daylight sources needs to be related to the occupant's preferences regarding the luminous distribution as well as the manner in which it is controlled by the building envelope. The accessibility of daylight sources to a specific area indoors needs to be related to site conditions, the plan and section of the building, and the flexibility of daylight apertures in the building envelope.

4.3 Glare and veiling reflections

	Correction	Prevention	Customisation
Luminanous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

An intelligent building envelope ideally avoids each building occupant from experiencing glare or veiling reflections, at any work area in the indoor environment. By determining whether glare sources appear in the occupant's visual field, and whether they indeed are experienced as such, the envelope may aim to achieve the following objectives:

- To correct glary conditions at the occupant's request
- To prevent glare and veiling reflections from arising
- To customise glare control according to the indivual occupant's wishes

4.3.1 Correction of glary conditions

At the occupant's request, an intelligent building envelope needs to be able to remove glare sources from the occupant's visual field, or reduce their impact so as to not be experienced as glary. Functional criteria related to the envelope's ability to correct glary conditions are listed in Figure 4-8.

Correction	Prevention	Customisation
• Monitoring strategy • Interpretation of user requests • Evaluation of response strategies • Correction of a glary daylight aperture • Correction of low adaptation luminance • Correction of reflected glare		

Figure 4-8: *Functional criteria related to the envelope's ability to correct glary conditions.*

• **Monitoring strategy.** As explained in Chapter 3, glare may be caused by an uneven or excessively bright primary or secondary light source in the occupant's visual field. In order to identify the specific light source that causes the occupant to experience glare, the envelope can monitor the luminance values and ratios in the occupant's visual field, particularly in and around the daylight apertures and task surface, and between the apertures and the rest of the room. Also the temporal variations in brightness need to be monitored, as they may have caused the occupant to experience glare by means of transient adaptation.

• **Interpretation of user requests.** Assessing which light source causes the occupant to experience glare is complicated for an intelligent building envelope, as glare may be induced by a large number of primary and secondary daylight sources in the occupant's visual field; also the adaptation luminance in the occupant's visual field needs to be taken into account. Furthermore, light sources with a high temporal luminance variation may generate glare perception more quickly than would stable light sources with high luminance, due to transient adaptation.

• **Evaluation of response strategies.** The building envelope can alter the visibility and brightness of the glare sources in the occupant's visual field by by adjusting the morphology of its daylight apertures. The appropriateness of the strategy the envelope chooses, depends on the relative size of the glare source in the occupant's visual field. When the occupant's visual field largely contains sky and site elements framed by the daylight aperture, this aperture will be the main means by which the envelope can influence the occupant's glare experience. When a large part of the occupant's visual field is occupied by indoor surfaces, on the other hand, an intelligent building envelope can include daylight apertures as well as indoor surfaces in its strategies to obtain less disturbing brightness ratios in the occupant's visual field.

• **Correction of a glary daylight aperture.** A daylight aperture may be identified as glary when it allows sky and site conditions with a high brightness level or ratio in the occupant's visual field. In this case, an intelligent building envelope can obstruct the occupant's line of sight to the glare source, and thus exclude it from the occupant's visual field. Alternatively, the brightness of the glare source can be reduced by lowering the visible light transmittance of the aperture across the entire aperture area, or only in the brightest zones of the aperture. The glariness of a daylight aperture may also be reduced by increasing the luminance of the envelope surfaces surrounding the aperture. This can be achieved by having the surrounding envelope surfaces reflect more incoming daylight, either by increasing the reflectance of the surface material, or by altering the angle of the surfaces relative to the solar incidence angle. Alternatively, the luminance contrast between the aperture and indoor surfaces may gradually be reduced by means of curving the transition surfaces, or by a gradual decline in surface reflectance.

• **Correction of low adaptation luminance.** A bright daylight aperture may also cause glare when seen from a task area with low adaptation luminance, typically situated at a distance from the aperture. An intelligent building envelope can attempt to increase the adaptation luminance by reflecting more light to those surfaces that influence the occupant's visual field. Care should be taken, however, not to cause reflected glare in the task area.

• **Correction of reflected glare.** Glare and veiling reflections may also be caused by a bright light source reflected off surfaces in the visual field, particularly in the task area, causing indoor surfaces to have a high brightness compared to the surrounding surfaces. this brightness difference can be due to a high or uneven reflection from daylight sources in the occupant's visual field, or to a distinct difference in reflection characteristics. Reflected glare in and around the task area can be removed by lowering the brightness of the aperture that causes this reflection to occur; alternatively, the aperture can be reshaped or relocated to prevent the incoming daylight from being reflected off surfaces in the task area.

4.3.2 Prevention of glary conditions

In addition to correcting glary conditions when they arise, an intelligent building envelope may actively attempt to prevent the occupant from experiencing glare. Functional criteria related to the envelope's ability to prevent glary conditions are listed in Figure 4-9.

Correction	**Prevention**	Customisation
	• Monitoring strategy • Prediction of environmental conditions • Prediction of envelope performance • Application of standard sky models • Application of standard lighting recommendations • Evaluation of response strategies	

Figure 4-9: *Functional criteria related to the envelope's ability to prevent glary conditions.*

• **Monitoring strategy.** With regard to glare induced by daylight, the daylight aperture may be considered to be the originator of all glare sources, either by making visible sun and sky and their bright reflections off surfaces on the site, or by causing bright reflections off indoor and envelope surfaces in the occupant's visual field. The luminance of the aperture, from the occupant's view angle, depends on a number of environmental conditions including the position and intensity of the sun, the prevalent sky type and cloud cover, their spatial and temporal variability, and the luminance of the site objects and surfaces framed by the aperture. The monitoring of these environmental conditions may be differentiated according to the orientation of the aperture with regard to climate and site, related to parameters such as the visibility and intensity of the sun, the site conditions that block or reflect sunlight, their position in the occupant's visual field, and the predicted stability of the cloud cover. Some of these conditions demand continuous monitoring, while for others periodical or situation-triggered measurements may suffice.

- **Prediction of environmental conditions.** In order to identify potential glare sources and their development in time, real-time measurements may be combined with the prediction of weather conditions. The weather forecast can be used to determine the prevalent sky type for that day, and more in particular the stability of the cloud cover and the correspondent visibility of the sun. This enables the envelope to assess the probable duration of the extreme brightness of potential glare sources, and to choose an appropriate strategy for avoiding or reducing the occupant's glare experience.

- **Prediction of envelope performance.** In addition, an intelligent building envelope needs to take care not to become a source of glare itself. Excessive brightness levels or ratios that are acceptable in natural circumstances might become unacceptable when they are brought forth by the envelope instead, as people are more tolerant towards glare from natural light sources than artificial ones, provided the glare remains within certain limits and logically relates to outdoor conditions.

- **Application of standard sky models.** Standard sky types and the layout of the site may be inserted into the envelope's memory for comparison to the real-time measurements. This information can be related to the presence of objects on the site that are prone to cause high brightness ratios under particular sky conditions, such as sun shimmering through vegetation, or a neighbouring building partially blocking sun.

- **Application of standard lighting recommendations.** The predicted development in environmental conditions and their impact on the luminance levels and variations then need to be assessed for their potential to cause the occupant to experience glare; to this purpose, real-time data may be compared to standard lighting recommendations. As mentioned in Section 4.2, however, these comparison is challenged by the adaptation of the occupant's eye to spatial and temporal luminance variations in its surroundings, and by inter- and intra-individual differences.

• **Evaluation of response strategies.** Having identified potential glare sources, an intelligent building envelope can proactively remove the glare sources from the occupant's visual field or reduce their impact so they will not be experienced as disturbing. On some occasions, however, the envelope may choose not to react when a risk of glare is perceived; for short-term glare risks, the adjustment in itself may disturb the occupant more than would the few seconds of exposure to glare. Nevertheless, when the occupant requests adjustments, the envelope should always react; if the required adjustments are regarded as unsuitable, the envelope should at least discuss this matter with the occupant.

4.3.3 Customisation of glare control

As people have a varying tolerance for glare depending on personal, task and environmental conditions, an intelligent building envelope may base its glare control strategies not only on standard lighting recommendations, but, above all, on the experience of the individual building occupant. Functional criteria related to the envelope's ability to customise glare control are listed in Figure 4-10.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Memorisation of occupant preferences • Customisation of glsre control

Figure 4-10: *Functional criteria related to the envelope's ability to customise glare control.*

• **Interpretation of occupant requests.** Personalised information regarding the occupant's sensitivity to glare in different environmental and task conditions will enable an intelligent building envelope to assess the glare risk for the individual occupant more appropriately. Feedback from the individual building occupants can be used to relate their glare sensitivity to the type of glare source, the time of day, and the specific activity they are performing during the glare experience. In addition, when notified of the occupant's increased glare sensitivity due to task or other reasons, the envelope may apply a more rigorous supervision of potential glare sources.

• **Memorisation of occupant preferences.** Adding personalised values of the occupant's glare sensitivity to the standard recommendations stored in its memory helps the envelope to identify potential glare sources for each individual occupant. Combined with real-time measurements and predictions, these preferences in addition allow the envelope to assess which parts of the outdoor environment will cause the lowest glare exposure over time and require the lowest amount of adjustments.

- **Customisation of glare control.** The building envelope can manipulate the intensity and directionality of incoming daylight directed to each indoor surface in order to even out excessive brightness ratios and to prevent the adaptation luminance from becoming too low or unstable. In addition, the envelope preferably chooses stable light sources over highly variable ones, as frequent variations in source luminance may cause transient adaptation and increase occupants' sensitivity to glare.

4.4 Colour

	Correction	Prevention	Customisation
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

An intelligent building envelope has the ability to manipulate daylight's colour appearance in the indoor environment, as this is influenced by the daylight sources admitted indoors and their reflections off in- and outdoor surfaces, though this effect is strongly attenuated by the human adaptation mechanism. Three main functions may be performed by the envelope in this context:

- To correct daylight's colour appearance at the occupant's request
- To prevent an inappropriate colour appearance of daylight indoors
- To customise daylight's colour appearance to the occupant's preferences

4.4.1 Correction of daylight's colour appearance

Daylight is considered to be the best light source for colour rendering; in addition, daylight's full spectrum distribution is indicated to improve occupants' visual satisfaction with the indoor environment and to influence the human metabolic system positively. Thus, in most situations, it is required of an intelligent building envelope to maintain daylight's colour appearance to the highest extent possible. On some occasions, however, for example on a dull day or during the performance of a specific task, the occupant may find daylight's colour appearance indoors inappropriate and wish to alter it. Functional criteria related to the envelope's ability to correct daylight's colour appearance indoors are listed in Figure 4-11.

Correction	Prevention	Customisation
• Monitoring strategy • Interpretation of user requests • Correction of colour appearance		

Figure 4-11: *Functional criteria related to the envelope's ability to correct daylight's colour appearance indoors.*

• **Monitoring strategy.** When the occupant requests that daylight's colour appearance indoors be altered, the envelope can identify the current conditions and their potential for change. Daylight's spectral distribution and colour temperature may be monitored either at the outdoor surface of the envelope, or indoors in the occupant's visual field. As explained in Chapter 3, however, human visual response does not register colour temperature the same manner a colorimeter would, as the human eye easily adapts to gradual differences in colour temperature in a room.

• **Interpretation of user requests.** Having received the occupant's request, in order to adjust the morphology of its daylight apertures accordingly, the envelope needs to assess whether the inappropriate colour appearance of daylight indoors may be caused by atmospheric conditions, by daylight's reflections off outdoor surfaces, or by the manner in which the envelope controls the admission and distribution of daylight sources indoors. While the human visual system in most cases attenuates differences in colour temperature both in space and time, particular circumstances such as abrupt variations in sky conditions, a strict distinction between direct sun and blue sky, and surfaces of high colour saturation, will be able to produce colour temperatures the human eye is able to distinguish. Furthermore, when daylight is transmitted through or reflected off envelope surfaces, its colour temperature tends to shift slightly; particular materials or abundant interreflections may alter daylight's colour appearance in a manner that is no longer perceived as corresponding to outdoor conditions, and cause dissatisfaction.

• **Correction of colour appearance.** If the inappropriate conditions are caused by atmospheric conditions, such as brownish air due to traffic pollution, the envelope may choose to manipulate the spectral distribution of its apertures according to the occupant's request. The envelope also needs to take into account the surfaces on the site daylight is reflected off on its path to the indoor environment; earth, for example, may provide a more brown-red tone to indoor surfaces [Baker *et al.* (ed.) 1993]. In addition, the envleope may create a particular indoor colour setting by reflecting incoming daylight off envelope or indoor surfaces with a strong saturation or chroma, in accordance with the occupant's request. On a dull day, for example, the envelope may cast light on coloured indoor surfaces to create a more cheerful mood, should this be desired by the building occupant.

4.4.2 Prevention of inappropriate colour appearance

The ability to predict variations in atmospheric conditions allows an intelligent building envelope to spot potential irregularities and take proactive measures. Functional criteria related to the envelope's ability to prevent an inappropriate colour appearance indoors are listed in Figure 4-12.

Correction	**Prevention**	Customisation
	• Prediction of environmental conditions • Prediction of occupant needs • Interpretation of anticipated environmental conditions • Evaluation of response strategies	

Figure 4-12: *Functional criteria related to the envelope's ability to prevent an inappropriate colour appearance indoors.*

• **Prediction of environmental conditions.** In order to assess the occurrence of potentially undesirable influences on the occupant's perception of colour indoors, the envelope may monitor the development of environmental conditions that exert a significant influence on daylight's colour temperature, such as solar intensity and position, cloud cover, water vapour levels, and atmospheric pollution.

• **Prediction of occupant needs.** People generally prefer indoor daylight conditions that logically relate to the local sky and site. If no particular requirements regarding colour appearance are specified, the envelope should thus remain as neutral as possible, providing light that corresponds to outdoor conditions. However, while daylight's natural variations in colour appearance may be desirable in the workplace, more irregular conditions such as man-made pollution may influence the colour appearance of indoor surfaces in a negative manner.

• **Interpretation of anticipated environmental conditions.** Information regarding the primary and secondary daylight sources in its environment allows an intelligent building envelope to assess the potential for emphasising or avoiding a specific colour appearance indoors. As mentioned in Chapter 3, the sky vault may display a large variation in colour temperature, and thus offers various possibilities for the envelope to influence the building occupant's perception of colour in the indoor environment. Direct sunlight, for example, has a colour temperature of around 7000 K and may cause indoor surfaces to appear slightly yellowish; diffuse skylight from blue cloudless sky patches, on the other hand, may have a colour temperature of beyond 20000 K and will cause indoor surfaces to appear more bluish [Baker *et al.* (ed.) 1993; Chain *et al.* 2001].

• **Evaluation of response strategies.** Unless stipulated otherwise, the envelope should attempt to influence the colour appearance of daylight indoors to the lowest extent possible. To this purpose, the envelope can reduce the number of interreflections needed for the light to reach a certain indoor area, and neutral surfaces may be used for the redistribution of daylight. When sky or site conditions threaten to alter the colour appearance of indoor surfaces in an undesirable manner, the envelope can adjust its morphology to mitigate this impact on the occupant's experience of colour indoors. Examples are the blocking of sunlight while blue skylight is admitted indoors, and the avoidance of undesirable reflections off neighbouring buildings. Inappropriate variations in daylight's spectral distribution over time, for example due to cloud cover, may be compensated for in a similar manner. Alternatively, the envelope may choose to slow down the outcome of those variations in order to give the human eye time to adjust to the new conditions.

4.4.3 Customisation of daylight's colour appearance

An intelligent building envelope can manipulate the occupant's perception of the colour of indoor surfaces by choosing particular light sources with a specific spectral distribution, position and extension. Functional criteria related to the envelope's ability to customise daylight's colour appearance indoors are listed in Figure 4-13.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Customisation of colour appearance

Figure 4-13: *Functional criteria related to the envelope's ability to customise daylight's colour appearance indoors.*

• **Interpretation of occupant requests.** In order to assess whether predicted environmental conditions are desirable, the envelope needs to know whether particular requirements regarding colour temperature are to be taken into account. During the execution of a particular task, for example, cool blue north light may be preferred, while on other occasions, yellowish sunlight may be welcomed indoors to provide a more cheerful environment.

• **Customisation of luminous distribution.** By altering the transmission and reflection characteristics of its apertures, an intelligent building envelope can determine which light sources to admit to the indoor environment, and which indoor surfaces to redirect them to. A small aperture, for example, may transmit light from a limited source area and with a very specific colour temperature. A larger aperture, on the other hand, may be influenced by a more extensive selection of sources, and thus transmit light that is more mixed and neutral. In a similar manner, the envelope can emphasise desirable colour effects that arise in the outdoor environment, or stress the variations that occur over time, by using apertures with distinct daylight sources.

4.5 Directional properties

	Correction	Prevention	Customisation
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

An appropriate mixture of directional and diffuse light offers suitable preconditions for visibility and creates a desirable atmosphere in the indoor environment. An intelligent building envelope can influence the directional properties of daylight in the indoor environment, aiming to achieve the following objectives:

- To correct daylight's directional properties indoors, at the occupant's request
- To prevent inappropriate directional properties of daylight indoors
- To customise daylight's directional properties indoors to user preferences

4.5.1 Correction of daylight's directional properties indoors

When the occupant signals dissatisfaction with the current lighting conditions, this is not necessarily due to illuminance levels or luminance ratios across the room; undesirable conditions may also arise due to the inappropriate directional properties of daylight indoors, created by a continuously shifting combination of direct sunlight, diffuse skylight and their reflections off surfaces in- and outdoors. Functional criteria related to the envelope's ability to correct daylight's directional properties indoors are listed in Figure 4-14.

Correction	Prevention	Customisation
• Monitoring strategy • Evaluation of response strategies • Providing directional light • Providing diffuse illumination		

Figure 4-14: *Functional criteria related to the envelope's ability to correct daylight's directional properties indoors.*

• **Monitoring strategy.** In order to correct the inappropriate conditions, the envelope first needs to assess the current situation, and identify the origin of the disturbance. To this purpose, the envelope can supervise the directional properties of daylight by means of the diffuse and beam illumination indoors at the task surface and other relevant areas in the occupant's visual field; the intensity and incidence angle of light, as well as their spatial and temporal variations, can be registered. Alternatively, diffuse and beam illumination may be measured at the outdoor envelope surface, and the correspondent intensity and incidence angle of illumination indoors calculated; this calculation, however, requires updated knowledge of the reflection characteristics of the indoor surfaces, relevant equipment and furnishings.

• **Evaluation of response strategies.** In order to respond to the occupant's request and adjust the directionality of illumination in the task area and other relevant surfaces in the occupant's visual field, the envelope needs to combine the effects the various types of daylight sources may provide. Direct beam sunlight can be used to add vitality to specific areas of the room, with variations according to cloud cover and the time of day; direct sun may also, however, create strong shadows and contrasts that interfere with visibility. Diffuse light may be used to even out such contrasts and shadows, and to create a more restful appearance in the indoor environment.

- **Providing directional light.** Light needs to be sufficiently directional in order to model three-dimensional objects and surfaces. By adjusting the morphology of its daylight apertures, the envelope can provide illumination with a strong vertical or horizontal component, should this be requested by the building occupant. In order to provide directional lighting, the envelope can make use of the natural incidence angle of the light, updating the morphology of its daylight apertures regularly to the variations in incidence angle of the sun and its reflections off surfaces on the site. Incoming sunlight may also be redirected elsewhere in the room by means of specular reflection, taking care to not create a source of reflected glare. At a relatively large distance from the daylight aperture, however, where daylight predominantly arrives with reduced directionality due to frequent interreflections, it may prove to be difficult to provide directional light. In such cases, the envelope needs to devise a strategy to minimise the diffusion of light before it reaches the required surface, for example by reducing the number of interreflections.

- **Providing diffuse illumination.** When more diffuse illumination is desired, the envelope can use diffuse skylight or light reflected off diffusing surfaces, and prevent direct sunlight from being admitted indoors. Alternatively, incoming daylight may be transmitted through or reflected off a diffusing material before being redistributed onto the task or other designated surface. If allowed by plan and section, daylight apertures may be created in multiple envelope surfaces in order to provide light from various angles and reduce shadows.

4.5.2 Prevention of inappropriate directional properties indoors

An intelligent building envelope may also attempt to prevent the occupant from experiencing daylight's directional properties indoors as unsuitable. Functional criteria related to the envelope's ability to prevent inappropriate directional properties of daylight indoors are listed in Figure 4-15.

Correction	**Prevention**	Customisation
	• Prediction of environmental conditions • Application of standard lighting recommendations • Interpretation of human visual response • Interpretation of anticipated environmental conditions	

Figure 4-15: *Functional criteria related to the envelope's ability to prevent inappropriate directional properties of daylight indoors.*

- **Prediction of environmental conditions.** The prediction of the development of the cloud cover and the correspondent visibility of the sun over time enables the envelope to assess their impact on the indoor environment, and to take measures before inappropriate conditions occur. The intensity and directionality of light penetrating the cloud cover depends on the type of clouds, their water content, density, and extension. A dense cloud cover in general displays a fairly uniform, though still varying, brightness; the solar area is the brightest. Most stable is a cloud cover that consists of more than one layer [Baker *et al.* (ed.) 1993]. Furthermore, sunlight's intensity and incidence angle display gradual and predictable changes due to the time of day and season. These data further need to be corrected for the influence of the surfaces and objects on the site.

- **The application of standard lighting recommendations.** The development of potential disturbances to the occupant may be detected by comparing the predicted values to standard lighting recommendations, particularly with regard to the task area. It is, however, difficult for an intelligent building envelope to maintain an overview of all factors related to the occupant's experience of directional and diffuse light in the indoor environment.

- **Interpretation of human visual response.** Variable sun- and skylight and their corresponding reflections off in- and outdoor surfaces cause ever changing modelling effects in the indoor environment, which, in addition, vary across the room, according to the geometry and materiality of indoor and envelope surfaces. The sensitivity of the occupant for the atmosphere, contrasts and shadows created indoors may also vary according to factors such as the task to be performed, the occupant's mood, and weather conditions.

- **Interpretation of anticipated environmental conditions.** The development of the cloud cover may cause large spatial and temporal variations in diffuse skylight and the visibility of the sun. Predicting the development of sky conditions does, however, allow the envelope to choose those primary and secondary daylight sources that provide the most stable conditions over time.

4.5.3 Customisation of daylight's directional properties indoors

The ability to learn the occupants' individual needs and preferences and to detect patterns in their daily behaviour helps an intelligent building envelope to create a personalised atmosphere indoors. Functional criteria related to the envelope's ability to customise daylight's directional properties indoors are listed in Figure 4-16.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Memorisation of occupant preferences • Customisation of directional properties

Figure 4-16: *Functional criteria related to the envelope's ability to customise directional properties of daylight indoors.*

• **Interpretation of occupant requests.** In order to create the desired modelling effects indoors, the envelope can take into account the occupant's visual field and and individual preferences. In addition, the envelope can identify the specific directionality required for a certain task in order to avoid the risk of unnecessarily reducing visibility; furthermore, the position of the work area, the inclination of the task surface, and its orientation related to the daylight apertures can be determined. In addition, the building occupant or the designer may have specified important surfaces due to their function or materiality.

• **Memorisation of occupant preferences.** Since the envelope in general can choose between several strategies to obtain a certain modelling effect in the indoor environment, it needs to also learn the type of strategy preferred by the building occupant in order to achieve a specific modelling effect and atmosphere.

• **Customisation of directional properties.** By adjusting the morphology of its daylight apertures, an intelligent building envelope can determine which daylight sources to reject or admit indoors; daylight's large temporal and spatial luminance variations will produce variable effects in the indoor environment, and the envelope needs to find daylight sources that provide natural variations within the tolerance limit of the occupant. Once allowed to enter the indoor environment, daylight needs to be guided to the appropriate areas and surfaces, and its directional properties altered if necessary. All surfaces in the indoor environment act as indirect sources of daylight, and the envelope may use their reflection characteristics to diffuse and redistribute daylight and create the required modelling effects. The suitability of indoor surfaces for this purpose is strongly influenced by their geometry and materiality, their distance and orientation towards the daylight apertures, and the position and morphology of the daylight apertures in the building envelope.

4.6 Visual contact with the outdoor environment

	Correction	Prevention	Customisation
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

The morphology of daylight apertures in the building envelope determines the kind of view a building occupant has of the sky and site conditions around the building, and the degree of privacy perceived. In this context, the building envelope may choose to perform several functions:

- To correct the degree of visual contact when requested
- To prevent the occurrence of disturbances due to visual contact
- To customise the degree of visual contact

4.6.1 Correction of visual contact upon request

Visual contact with the outdoor environment is a substantial factor for the well-being of the building occupants; however, at particular times, the possibility to shield themselves from the outdoor environment may be just as important. Functional criteria related to the envelope's ability to correct the occupant's degree of visual contact with the outdoor environment are listed in Figure 4-17.

Correction	Prevention	Customisation
• Monitoring strategy • Interpretation of user requests • Interpretation of envelope performance • Evaluation of response strategies • Correction of visual contact		

Figure 4-17: *Functional criteria related to the envelope's ability to correct the occupant's degree of visual contact with the outdoor environment.*

- **Monitoring strategy.** When a change of scenery is requested, the envelope needs to assess the current degree of connection to or separation from the outdoor environment the building occupant experiences as a consequence of the morphology of daylight apertures in the building envelope, related to the occupant's position and view angle in the room.

- **Interpretation of user requests.** Not only the degree of contact, but also the variability of sky and site elements, or the lack of such, may cause disturbance. The presence and activities of people outdoors and in neighbouring buildings, for example, exert a considerable influence on the occupants' opportunity to shield themselves from the outdoor environment. Or, reversely, the occupants may welcome a view to exhibit variability such as outdoor activities and be dissatisfied if this opportunity is not provided by the envelope.

- **Interpretation of envelope performance.** As the sky and site cannot be altered, the cause of the occupant's dissatisfaction lies most likely with the manner in which the building envelope is controlling the situation. The envelope needs to assess its own morphology for the manner in which it restricts or distorts the view, and for the degree of exposure to the outdoor environment it causes the occupant to experience. It may, for example, irritate the building occupant to be deprived of a view containing nature, when this view is available on the site.

- **Evaluation of response strategies.** The envelope's potential for creating a view with satisfactory depth, composition and variability depends on its orientation in relation to sky and site conditions; in addition, the occupant's position and view angle, as well as any obstructions due to furnishings and fixtures in the indoor environment need to be taken into account. Furthermore, occupant requests for a view or privacy always need to be combined with the daylighting requirements that are to be taken into account at all times. The envelope thus needs to assess the possibilities for responding to the occupant's request appropriately within this setting.

- **Correction of visual contact with the outdoor environment.** By adjusting the position of its daylight apertures, an intelligent building envelope can determine which parts of the outdoor environment are visible from a particular position and view angle of the building occupant. In general, daylight apertures can be positioned in the facade (*lateral apertures*) or in the roof (*zenithal apertures*). Lateral apertures offer the best preconditions for a view to the outdoor environment; zenithal apertures or apertures above eye height do not provide a view, but do give the occupant some information about the time of day and weather conditions [Baker *et al.* (ed.) 1993]. Also the size of a daylight aperture significantly influences the occupant's experience of visual contact with the outdoor environment. A small aperture may offer interesting accents but provoke a feeling of being locked in; a large aperture, on the other hand, provides a more panoramic view, but may cause the building occupant to feel exposed to passers-by and people in the neighbouring buildings. The size of an aperture also needs to be related to the distance between the building occupant and the aperture.

4.6.2 Prevention of unsatisfactory visual contact

Predicting the nature and variability of the sky and site conditions framed within the daylight apertures offers an intelligent building envelope the opportunity to assess the suitability of the view provided to the building occupant, and take proactive measured in case disturbances are expected. Functional criteria related to the envelope's ability to prevent the occupant from experiencing unsatisfactory visual contact with the outdoor environment are listed in Figure 4-18.

Correction	**Prevention**	Customisation
	• Prediction of environmental conditions • Application of site models • Application of standard recommendations • Interpretation of human visual response • Interpretation of anticipated environmental conditions	

Figure 4-18: *Functional criteria related to the envelope's ability to prevent the occupant from experiencing unsatisfactory visual contact with the outdoor environment.*

• **Prediction of environmental conditions.** A first type of information regarding the environment and its impact on the occupant's view and privacy consists of the development of weather conditions, with their spatial and temporal variations.

• **Application of site models.** Fairly stable site elements, such as neighbouring buildings blocking view, can be inserted into the envelope's memory and updated regularly in order to simplify their identification. Variable elements, such as the presence and activities of people outdoors and in neighbouring buildings, are more difficult for the envelope to identify.

• **Application of standard recommendations.** Potentially unsatisfactory conditions may be detected by comparing the predicted environmental conditions to general recommendations on the nature and degree of contact between building occupants and the building's outdoor environment. In general, for example, people prefer a view to contain foreground as well as skyline; in most situations, a view is also preferred to be complex, including ground surfaces and activities. Concurrently, building occupants generally won't accept a distorted or restricted view. Equipment and furnishings in the indoor environment and the building envelope may obstruct a view from the occupant's position and view angle. Multiple layers in the building envelope may cause the occupant to feel distanced from the outdoor environment or produce a feeling of confinement.

- **Interpretation of human visual response.** While general guidelines for the type of view preferred by people do exist, it is difficult for the envelope to discern the specific preferences of an individual related to the particular site without feedback from the building occupant, as there exist considerable inter- and intra-individual differences, as discussed in Chapter 3. In addition, view issues may collide with an occupant's personal preferences regarding privacy, for example when being exposed to passers-by. A similar assessment needs to be made for cases where several people occupy the room simultaneously; their needs regarding view and privacy are most likely to diverge due to different position in the room, individual preferences and the nature of the task they are performing.

- **Interpretation of anticipated environmental conditions.** An intelligent building envelope needs to consider carefully which changes in the environment it should react to; frequent or seemingly superfluous alterations may cause irritation. Making adjustments whenevers building occupant turn their heads or stand up, for example, is unnecessary; such margins may rather be attempted included in the envelope's strategies to find a suitable aperture morphology.

4.6.3 Customisation of visual contact to the individual occupant

An intelligent building envelope needs to be able to compose a satisfactory view for the building occupant, adjusted to the position and orientation of the workplace in the room, and in accordance with the occupant's needs and preferences for contact with the outdoor environment. Functional criteria related to the envelope's ability to customise the occupant's visual contact with the outdoor environment are listed in Figure 4-19.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Memorisation of occupant preferences • Customisation of visual contact

Figure 4-19: *Functional criteria related to the envelope's ability to customise the occupant's visual contact with the outdoor environment.*

• **Interpretation of occupant requests.** The envelope can provide desirable views while taking into account the occupant's need for privacy and shielding from the outside world. To this purpose, the envelope needs to identify and assess the nature and variability of elements on the site that may influence the occupant's experience of view and privacy. Also task-related conditions influence the occupant's specific needs and preferences regarding view and privacy, and the particular demands an occupant poses in relation with the performance of a certain type of task can be registered by the envelope. This information then needs to be related to the occupant's particular position, eye height and view angle in order to determine which sky and site areas may occur within the occupant's visual field.

• **Memorisation of occupant preferences.** In order to provide good indoor daylighting quality, an intelligent building envelope can use the feedback and instructions received from the building occupant to learn the nature and degree of visual contact with the outdoor environment is preferable, tolerated or rejected by a particular building occupant in diverse ambient and task-related conditions.

• **Customisation of visual contact.** An intelligent building envelope can adjust the morphology of its daylight apertures in order to provide the degree of visual contact with the outdoor environment desired by the building occupant. For sedentary and monotonous work, for example, an extensive view tends to be highly regarded. In such cases, the envelope may provide a large transparent aperture area in the occupant's visual field, containing several interesting and variable elements. When, on the other hand, deep concentration or a high degree of privacy is required, the envelope can still provide an aperture higher up in the wall, or in the ceiling, allowing a view to the sky and a sense of changing weather conditions.

4.7 Individual control

	Correction	Prevention	Customisation
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

The possibility for building occupants to influence their own luminous work environment often has a positive psychological effect on them; the need to actually exercise control, however, may also induce stress and lack of concentration.

An intelligent building envelope thus needs to assess the nature, extent and timing of its actions carefully, and find a balance between exercising control according to the occupant's needs and preferences on the one hand, and giving the occupant the opportunity to influence these control actions on the other hand. In this context, the envelope may influence the occupant's experience of control in three manners:

- To correct the occupant's feeling of control, at the occupant's request
- To prevent the occupant from experiencing a reduced feeling of control
- To customise the occupant's experience of control to individual preferences

4.7.1 Correction of occupant control

As explained in Chapter 2, an occupant may be given a certain degree of control over indoor luminous conditions (*situation state*) and, potentially, over the manner in which those luminous conditions are achieved (*control state*) [Willey 1997]. Functional criteria related to the envelope's ability to correct the occupant's experience of control over the luminous environment are listed in Figure 20.

Correction	Prevention	Customisation
• Interpretation of user requests • Interpretation of envelope performance • Communication with building occupant		

Figure 4-20: *Functional criteria related to the envelope's ability to correct the occupant's experience of control over the luminous environment.*

• **Interpretation of user requests.** When the occupant is dissatisfied, the envelope needs to find out whether this is caused by the nature and extent of control the occupant is allowed to exercise. A first cause for dissatisfaction may be a lack of *cognitive control* over the luminous environment. The occupants may experience that their preferences regarding indoor luminous conditions do not influence the envelope's actions in this field, i.e., a lack of control over the *situation state*. Similarly, the occupant may be dissatisfied with a perceived lack of influence over the *control state*, or the nature, timing and frequency of actions the envelope undertakes in order to influence luminous conditions and provide good indoor daylighting quality. Another reason for dissatisfaction is related to *behavioural control* or the necessity of actually having to exercise control while they do not want to. As discussed in Chapter 3, most occupants do prefer to have control options available; having to use them frequently, however, may actually reduce the occupant's performance and perception of indoor daylighting quality.

• **Interpretation of envelope performance.** An intelligent building envelope needs to react to environmental conditions that are disturbing to the building occupant, while avoiding to become a source of irritation itself.

• **Communication with the building occupant.** The envelope can provide the building occupants with information on the consequences of their requests. When occupants make a poor choice or one that is impossible to fulfil, the envelope can inform them of the anticipated effect of their choice, and offer an alternative solution. However, the occupants should always have the last word and be given the possibility to override the envelope's decision.

4.7.2 Prevention of reduced occupant control

Regardless of an intelligent building envelope's ability to take into account all environmental changes and adapt to them even before they are experienced by the occupant, the latter should always feel in control over the situation. Functional criteria related to the envelope's ability to prevent the occupant from experiencing a reduction of control over the luminous environment are listed in Figure 4-21.

Correction	**Prevention**	Customisation
	• Prediction of environmental conditions • Interpretation of human visual response • Interpretation of envelope performance • Evaluation of response strategies	

Figure 4-21: *Functional criteria related to the envelope's ability to prevent the occupant from experiencing a reduction of control over the luminous environment.*

• **Prediction of environmental conditions.** An intelligent building envelope needs to be able to perceive conditions related to individual control that may be discomforting to the building occupant. The ability to anticipate the development of environmental conditions and their impact on indoor daylighting quality helps the envelope to avoid the use of daylight sources that will reduce the occupant's experience of control over the luminous environment. The nature of the daylight sources as well as their spatial and temporal variations are important in this respect.

• **Interpretation of human visual response.** As discussed in the previous sections, each person has varying needs and preferences regarding indoor luminous conditions, requiring for occupants to adapt their own luminous environment. The nature and extent of control required by each occupant for diverse luminous conditions, however, will vary according to vision, age, activity, and individual preferences, making it difficult for the envelope to take general proactive measures.

• **Interpretation of envelope performance.** The introduction of measures the occupants did not ask for, as well as frequent proactive measures where the envelope continuously adapts itself to potentially disturbing conditions without the occupants actually experiencing them, may diminish the occupants' feeling of control over their environment and are thus preferably avoided. The introduction of increased illuminance levels at certain times of day, for example, was in Chapter 3 reported to be successful, but only when introduced at the occupants' own choice; otherwise, such measures were considered to be a stressor in the work environment [Cakir & Cakir 1998].

• **Evaluation of response strategies.** The envelope needs to provide the building occupant with a feeling of control over the luminous environment. To this purpose, the envelope can communicate with the building occupant, and avoid actions the building occupant may regard as illogical or irrelevant. Some envelope tasks may, for example, require devices to be located on the envelope's exterior or in between two envelope layers, out of the occupant's reach. Also multiple envelope layers may reduce the occupant's feeling of control, particularly when actions such as opening a window do not allow for direct contact with outdoor air.

4.7.3 Customisation of occupant control

An intelligent building envelope needs to provide the building occupants with a feeling of control over their luminous environment. By learning the occupants' preferences and acting accordingly, the envelope can allow them to feel in control without actually having to exercise it - unless they prefer to. Functional criteria related to the envelope's ability to customise the occupant's experience of control over the luminous environment are listed in Figure 4-22.

Correction	Prevention	**Customisation**
		• Interpretation of occupant requests • Memorisation of occupant preferences • Customisation of occupant control

Figure 4-22: *Functional criteria related to the envelope's ability to customise the occupant's experience of control over the luminous environment.*

• **Interpretation of occupant requests.** An intelligent building envelope can register the nature, frequency and timing of the occupant's interventions in situation and control state, along with the environmental conditions during which the interventions take place. In addition, the envelope can monitor the occupant's feedback to actions performed by the building envelope; relevant features, in this context, are the nature and extent of the envelope actions, as well as the timing and frequency with which they occur. The occupant's feedback may also consist of overruling envelope actions, or in another way attempting to exercise behavioural control (i.e., physically adjusting the daylight apertures).

• **Memorisation of occupant preferences.** The envelope needs to learn the maximum range and frequency of adjustments an occupant is willing to accept when performing a certain type of task, along with the type of adjustments the occupants prefer to perform personally.

• **Customisation of occupant control.** An intelligent building envelope can choose daylight sources that best enable it to comply with the individual needs of the building occupant, thus providing the occupant with a sense of cognitive control even without physically exercising it. To this purpose, the envelope needs to use daylight sources that require a type, frequency and timing of control the envelope is able to provide and that is accepted by the building occupant. When several people are occupying the room simultaneously, the occupants' control over their work environment needs to be limited. On such occasions, an intelligent building envelope can process all available information on the occupants' preferences and attempt to find a reasonable balance between divergent demands, without infringing on anyone's feeling of control.

• **Communication with building occupant.** In addition, the envelope can communicate with the building occupant in order to gain a better understanding of the latter's preferences and to increase the occupant's comprehension of the various choices the envelope needs to make. The building occupants can, for example, be given information on the current and anticipated status of daylighting quality in their office in the form of diagrams, charts, or a text box. When several alternatives for action are equally relevant, the envelope can present the occupants with this range of options and invite them to choose one, thus updating its knowledge on the occupants' preferences. This type of communication, however, is preferably only used when the occupant actually shows any interest in taking part in the decision making process, and not has stated any preference of rather to be left alone.

5 Physical application: envelope intelligence for daylighting quality

5.1 The implementation of intelligence in the building envelope

In building practice, the functions analysed in Chapter 4 need to be interpreted physically into envelope materials, components and systems. The use of material and form in these applications, their flexibility, and their connection to the envelope all influence an intelligent building envelope's ability to adapt to its environment and to create an indoor luminous environment correspondent to occupant requirements.

Chapter 5 analyses a selection of physical applications for their impact on envelope performance with regard to daylighting quality, and evaluates their strengths and weaknesses for application in an intelligent building envelope (Figure 5-1).

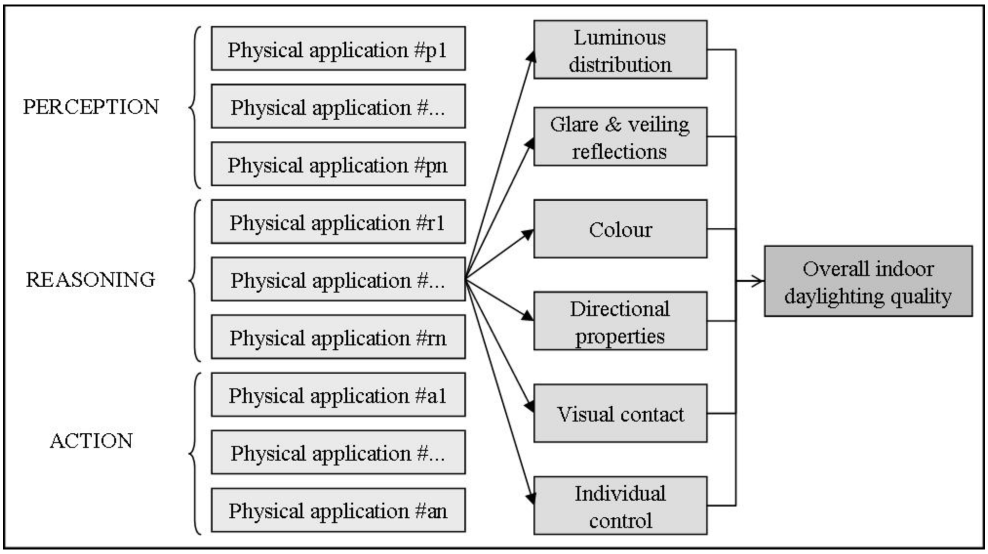
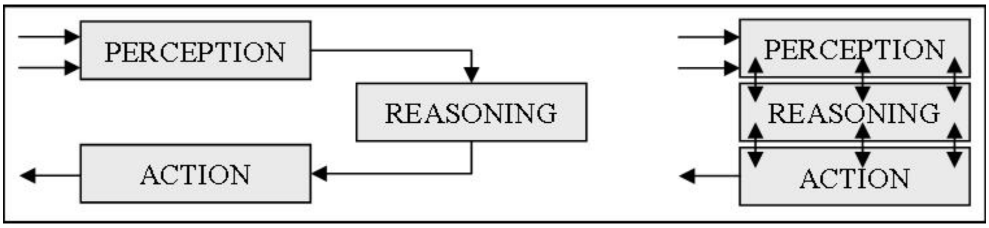


Figure 5-1: *In Chapter 5, each physical application is analysed for its influence on luminous and contextual conditions related to daylighting quality. The selection of physical applications is organised in three groups: perception, reasoning and action.*

With limited resources, an intelligent building envelope needs to look for ways in which to make its performance more efficient and effective. Each physical application, implemented to perform a particular function, simultaneously restricts the manner in which this function can be performed, and, in addition, creates *side effects* on the performance of other envelope functions. Luminous conditions share amongst each other several variables that, on the one hand, may mutually enhance each other and enable the envelope to work more efficiently, and, on the other hand, create conflicts, according to the particular physical application that is chosen.

The structure of this chapter aims to stress the interaction and potential conflicts between diverse luminous and contextual conditions that arise in the functioning of a specific physical application. Originally, a structure similar to that of Chapter 4 was intended, where for each of the functions required for daylighting quality, a selection of physical applications is presented and evaluated. This approach, however, does not identify the areas of conflict and mutual enhancement that arise between the different functions when performed simultaneously by the building envelope. Therefore, it was chosen to evaluate each physical application for its impact - intended and unintended - on all of the functions described in Chapter 4 (Figure 5-1).

A similar approach was intended for the manner in which each of the applications, within an intelligent building envelope, works with perception, reasoning and action processes, either as a multifunctional element, or as a multi-layered system, where all elements are designed for close co-operation with each other (Figure 5-2).



From [Neumann 1999:6]

Figure 5-2: *Processes of perception, reasoning and action in an intelligent building envelope; (left) organised as a conventional system, where perception, reasoning and action processes are performed consecutively and by distinct materials or components; (right) organised as an integrated, multifunctional system, with perception, reasoning and action processes integrated within one material or component, or as a multi-layered system where all elements are designed in close co-operation with each other.*

The application of elements that integrate perception, reasoning and action processes, however, turns out to be less frequent than first assumed; the majority of applications is easily divided in three distinct groups of perception, reasoning and action processes, respectively. This is reflected in the structure of Chapter 5:

- The implementation of *perception*
- The implementation of *reasoning*
- The implementation of *action*

Chapter 5 features a selection of illustrative examples rather than a complete taxonomy - within the scope of this chapter, it is not possible to cover the wide range of materials, components and systems that may be applied in an intelligent building envelope. The examples are chosen because of their flexibility, their degree of detail in material use and form, and the particular care with which they have been composed within the building envelope. By no means, however, does this imply that there do not exist other successful approaches to the issues discussed in Chapter 4.

5.2 The implementation of perception

Section 5.2 covers elements that perform perception processes. These materials and components are applied in an intelligent building envelope in order to help it collect information and feedback regarding:

- The state of the in- and outdoor environment
- The needs, preferences and behaviour of the building occupant
- The outcome (main and side effects) of envelope actions

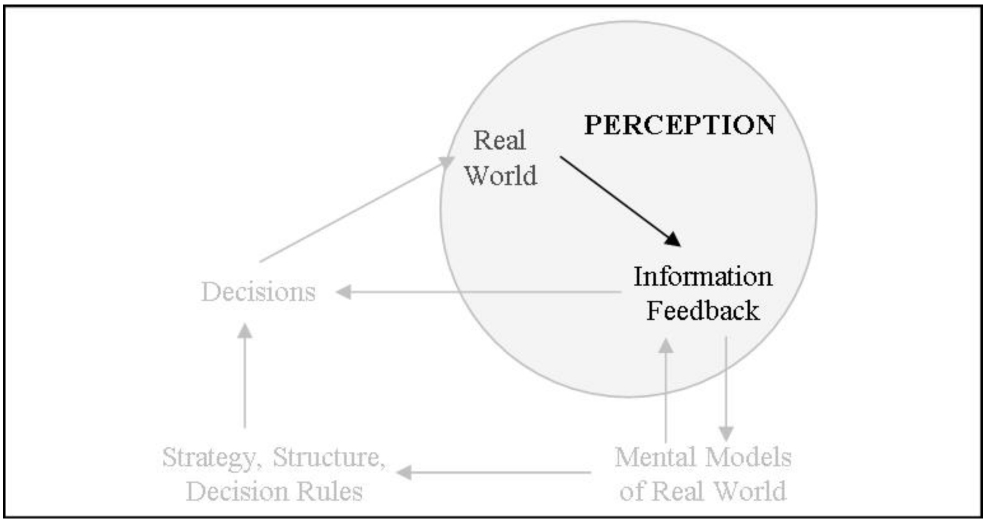


Figure 5-3: *Perception processes help an intelligent building envelope collect information regarding the indoor luminous environment, the outdoor environment, the building occupant, and the building envelope's own performance.*

To be monitored are environmental conditions, with their variations in time and space, and occupant needs and preferences. Important are not only the type of variables, but also the place in which they are monitored, and the frequency with which this occurs: continuously, periodically or occasionally, when a need for change is detected. Section 5.2 covers these issues within two main areas of application:

- Perception of environmental conditions
- Perception of occupant information

5.2.1 Perception of environmental conditions

The physical applications that provide an intelligent building envelope with information, do not necessarily need to be physically connected to the envelope surface; perception of environmental conditions may occur in the indoor environment, at the envelope surface, or in the outdoor environment. In Section 5.2.1, the following three types of physical applications are discussed:

- Photosensor
- Sky scanner
- Geostationary satellite

5.2.1.1 Photosensor

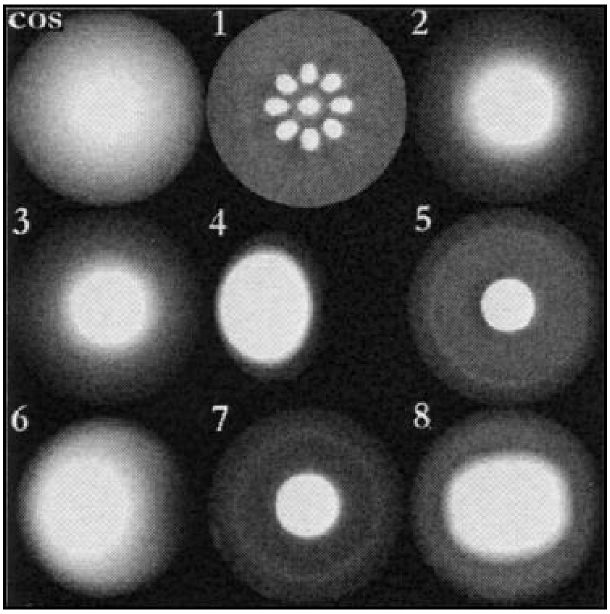
In general, a photosensor can be described as a component that registers visible radiation; it typically consists of a silicon photodiode and a diffuser that integrates the luminance of the surfaces within the opening angle of the light-sensitive cell [Ehrlich *et al.* 2002].

Photosensors can be used to monitor beam and diffuse illumination on the task surface, across the room, and on the envelope surface. In this context, they are often used in co-operation with daylight-linked artificial lighting controls, where artificial lighting is dimmed according to the daylight available for ambient and task lighting.

Measurements of photosensor illuminance can further be used to indicate glare risk, for example with regard to luminance ratios between the daylight aperture and the surfaces surrounding the task surface. However, the assessment of glare risk by means of photosensors would require a considerable number of sensors to be positioned in the occupant’s visual field.

The successfulness of this type of component in monitoring illuminance levels depends on several factors, among which are the spatial and spectral sensitivity of the photosensor, its location and opening angle, and the sky conditions during which the calibrations of the equipment occur:

• **Spatial sensitivity.** The spatial response of a photosensor is of the utmost importance, as this determines how the luminance of the surrounding surfaces influences the illuminance levels measured by the photosensor. Bierman & Conway present eight examples of how the spatial sensitivity of photosensors may vary between photosensors, with variations in the size of the opening angle as well as in its symmetry (Figure 5-4) [Bierman & Conway 2000, in Ehrlich *et al.* 2002].

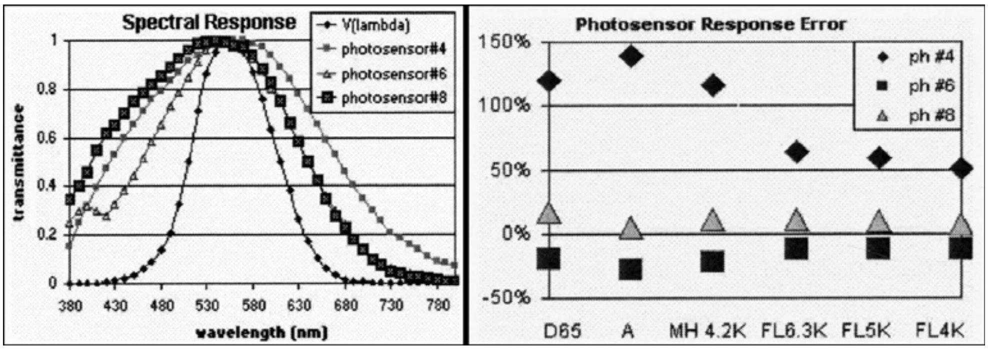


[Bierman & Conway 2000, in Ehrlich *et al.* 2002:884]

Figure 5-4: *The spatial sensitivity of photosensors may vary considerably. On the upper left, an ideal cosine spatial sensitivity distribution is shown. Numbers 1 to 8 depict diverging spatial responses.*

• **Spectral selectivity.** As the spectral selectivity of a photodiode is different from the spectral selectivity of the human eye, photodiodes are generally equipped with a filter to correct their spectral selectivity towards that of the human visual response.

According to Ehrlich *et al.* [2002], however, the use of colour-correction filters is not always equally successful (Figure 5-5); spectral selectivity may vary among photosensors, as well as for the individual photosensor according to the type of light source used.



[Ehrlich *et al.* 2002:885]

Figure 5-5: *The use of colour-correction filters is not always equally successful; (left) three representative photometric correction filters compared to the CIE 1924 V-lambda photometric curve, an ideal colour-correction used to convert spectral radiance according to the spectral sensitivity of the human visual response; (right) relative error of three representative spectral curves illuminated by daylight (D65), incandescent (A), 4200K metal halide (MH 4.2K), 6300K fluorescent (FL 6.3 K), 5000 K fluorescent (FL 5 K), and 4000 K fluorescent (FL 4 K).*

- **Location & opening angle.** It is challenging to find an appropriate location for the sensor, and a reference plane for the sensors to be aimed at. For the monitoring of illuminance levels on the work surface, for example, a photosensor is typically positioned on the ceiling, and its maximum response aimed towards the task. The sensor, however, perceives not only the task surface, but also the luminous distribution across surrounding surfaces, the extent of which depends on the sensor's spatial response and opening angle. In addition, the sensor's perception may be disturbed by furnishings, fixtures and fittings reducing the view to the reference plane, by changes in surface reflectance due to papers, books and other objects lying around, and by the presence of an extremely bright surface, such as a daylight aperture, in the sensor's acceptance angle [Ehrlich *et al.* 2002; Schmitz 2001]. An additional challenge is related to the measurement of diffuse illumination, which may be strongly anisotropic. When the acceptance angle of the sensor in addition includes a daylight aperture, and direct sun is present, it is difficult to measure diffuse illumination alone. To this purpose, a shadow ring is used to shade the sensor from direct sun [Li *et al.* 2005].

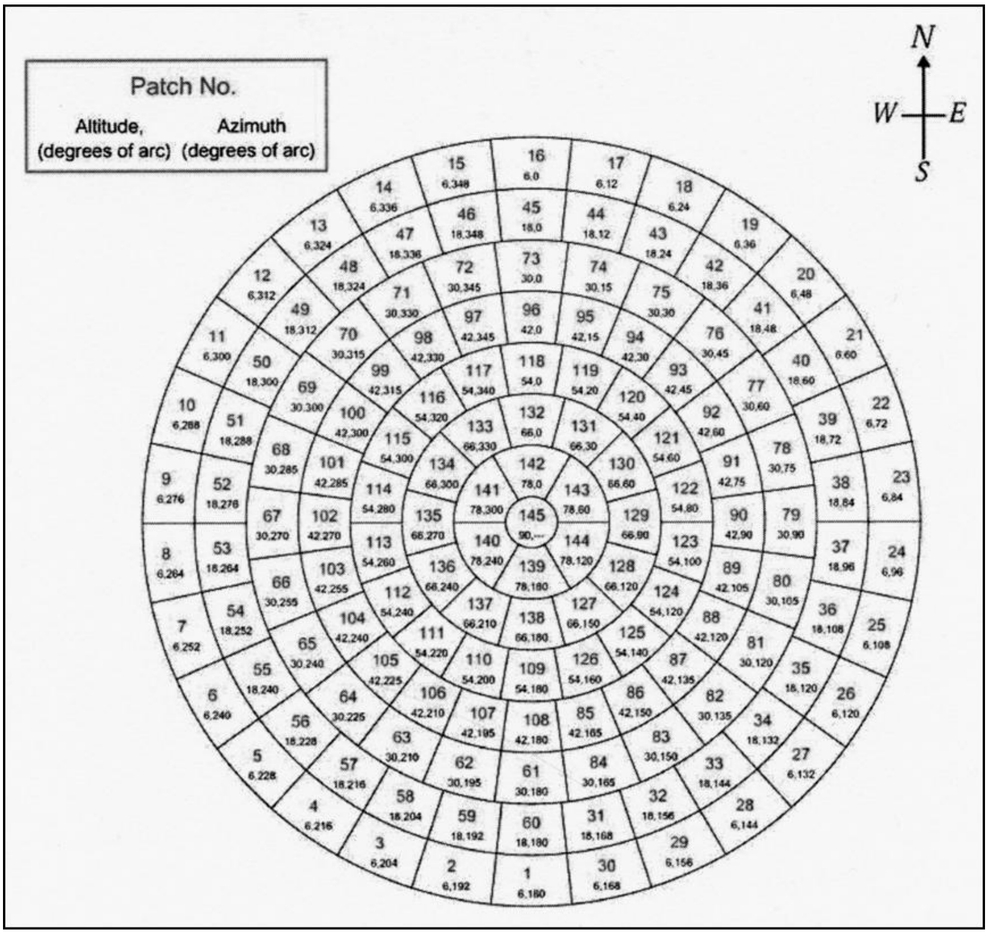
- **Calibration & maintenance.** After installation, the sensor needs to be calibrated in order to optimise its operation to local conditions. The sky conditions during which the calibrations take place play an important part in the successfulness of the sensor's performance. As real-time sky conditions under which the sensor needs to operate always will diverge from the sky conditions during which the calibrations took place, the sensor needs to be calibrated under a wide variety of sky conditions in order to improve the accuracy of its performance. This is a time-consuming and costly operation [Choi *et al.* 2005; Ehrlich *et al.* 2002]. In addition, there is a degradation of sensor performance due to age, potential failures that need to be detected by the building envelope, and the influence of (lack of) cleaning and maintenance. Preferably, several sensors can be used simultaneously in order to verify the data and compensate in case of degradation or error.

Unsatisfactory accuracy and deviations in performance between the different photosensors make their use in daylighting control systems less reliable. As the factors mentioned above form an important hinder to the successful application of photosensors, intensive research efforts are being made to reduce and map the variety that occurs among photosensors, and to find methods for modelling and predicting photosensor performance. Examples can be found in the work of Bierman & Conway [2000], Choi *et al.* [2005], Ehrlich *et al.* [2002], and Li *et al.* [2005].

In order to increase the reliability and accuracy of the sensed data, it is also possible to use a *multiple-sensor fusion* technique in order to retrieve data from various sources, compare them to each other, and then combine and abstract them into information. This procedure is described by, amongst others, de Silva [1995] and Sasiadek [2002]. Multiple-sensor fusion requires the use of soft computing algorithms such as fuzzy systems, artificial neural networks and evolutionary algorithms, which are discussed in Section 5.3.

5.2.1.2 Sky scanner

A sky scanner is a component primarily used to measure the sky luminance distribution in a grid of points across the sky dome (Figure 5-6). The grid is typically based on the 145-point grid for luminance measurements of the sky hemisphere, proposed by Tregenza for the International Daylighting Measurement Program [Tregenza 1987]. The measurements take place outdoors, which makes it necessary for the equipment to be weather-proofed. In addition, an automatic shutter comes into operation when a maximum luminance level is surpassed, for example for measuring points in the vicinity of the sun.



[Li *et al.* 2005:1652]

Figure 5-6: *Measurements for the sky scanner.*

In a project by Li *et al.* [2005], a sky scanner is used to measure sky luminance in a grid of 145 points across the sky dome, where each scanning sequence lasts around four minutes, and measurements are repeated every ten minutes. The highest luminance level that can be registered by the scanner is 35 Kcd/m^2. The measurement data can, amongst others, be used to predict illuminance levels on vertical and other inclined surfaces.

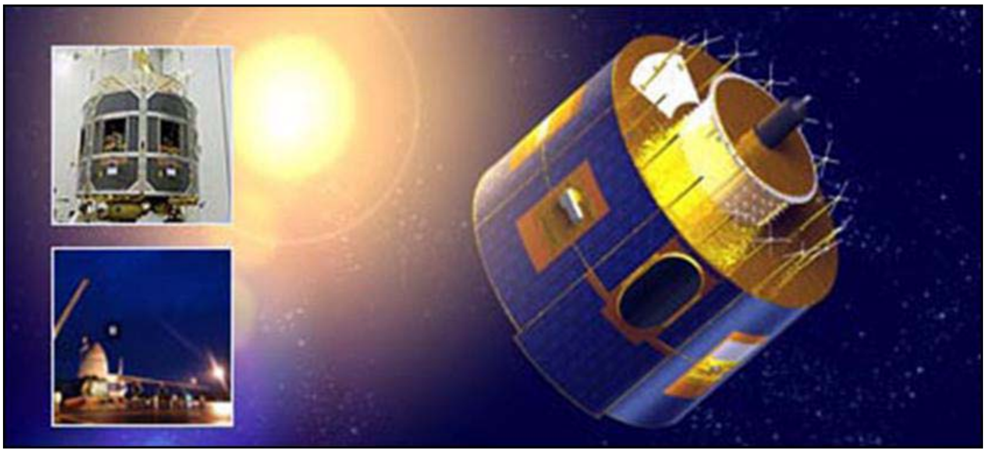
A similar scanning pattern may be applied by an intelligent building envelope to measure the luminance distribution across the site and sky for a particular daylight aperture. In this context, the scanner could be used to detect potential glare sources, and to identify primary and secondary daylight sources appropriate for use in the envelope's daylighting strategies. There are, however, some challenges to the integration of such data in the envelope's strategies, particularly related to the spatial and temporal continuity of the measured data:

- **Spatial continuity.** For each of the 145 points on the sky dome, a circular measurement is made. This leads to gaps between the measured points, where luminance only can be interpolated from the measured values. Luminance values exceeding 35 Kcd/m^2 are not registered correctly either.

- **Temporal continuity.** The luminance values in the measuring points are not monitored continuously, but with certain intervals. In highly variable sky conditions, the luminance distribution of the sky may change considerably in the time period between two measurements. This poses a considerable problem, particularly with relation to the detection of potential glare sources and transient adaptation.

5.2.1.3 Geostationary satellite

In addition to measuring the luminous distribution locally, information regarding the state of the outdoor environment, and particularly the development in time and space of atmospheric conditions, may be obtained by means of remote sensing, where perception takes place in a remote location such as a geostationary satellite (Figure 5-7) and the information is transmitted as requested.



[http://www.satellight.com]

Figure 5-7: *The Meteosat Second Generation (MSG) geostationary satellite.*

The remote sensing of atmospheric developments may be used to determine the prevalent sky type in the near future, and more particularly the stability of the cloud cover and the correspondent visibility of the sun. In addition, anticipated weather data can be utilised to calculate the optimum long-term strategies for heating, lighting and shading. Furthermore, data from geostationary satellites can be used to detect snow cover, an environmental condition that can pay a considerable contribution to the reflection of daylight indoors.

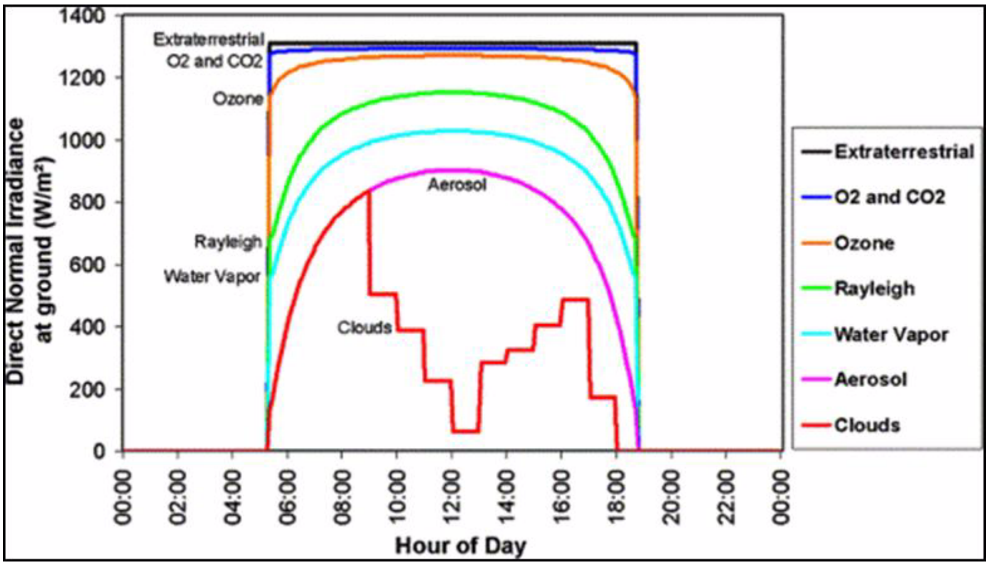
The remote collection of data gives an intelligent building envelope the opportunity to make its information on environmental conditions more complete. There are, however, considerable challenges with regard to the temporal and the spatial resolution of the data:

- **Temporal resolution.** The information collected by means of remote sensing can be used to predict the development of environmental conditions and to optimise long-term strategies accordingly. The data, however, are not accurate enough for real-time interaction with environmental changes.

- **Spatial resolution.** The remote data need to be adjusted for the particular microclimate and site the envelope and the rest of the building is located in, requiring the use of accurate models, and additional resources for calculations. Advantages of remote sensing, on the other hand, are the centralised verification of data, calibration of equipment, and provision of cleaning and maintenance services.

There exist different approaches for transforming satellite data into irradiance and illuminance information. Two of those, a physical approach and a statistical approach, are briefly discussed in the following paragraphs. Both methods use soft-computing algorithms such as fuzzy logic and artificial neural networks to process the collected data; these and other reasoning techniques are discussed in Section 5.3.

- **Physical approach.** Satellite data may be used to calculate hourly solar direct normal irradiance with a high spatial and temporal resolution, taking into account the influence of atmospheric constituents such as ozone, aerosols and water vapour, in addition to cloud cover. Among those, cloud cover is the most influential factor, as it may completely obstruct direct solar radiation from reaching ground surfaces; in addition, it is a highly variable factor (Figure 5-8). The physical approach is, amongst others, described by Schillings *et al.* [2004], with satellite data obtained from the geostationary Meteosat weather satellites. The authors assess the development of the cloud cover by comparing current satellite data on IR and visible solar radiation to a reference base made up of previously retrieved information. This assessment is made with the help of fuzzy logic techniques that, in addition, allow the system to learn and update its memory or reference base according to the developments in cloud cover over time. The application of this technique further simplifies the detection of thin cirrus clouds as well as data retrieval at low solar angles.



[Schillings *et al.* 2004:477]

Figure 5-8: *An example of daily irradiance variation data obtained by remote sensing, showing the influence of the different atmospheric constituents.*

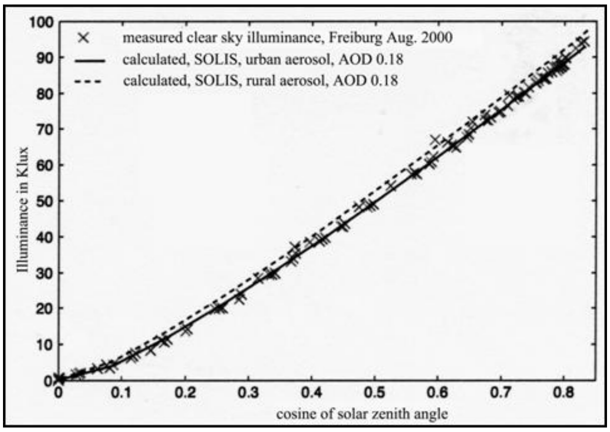
Meteosat data are also used by Mueller *et al.* [2004] to calculate global, direct and diffuse irradiance. As opposed to the work of Schillings *et al.*, the ozone, water vapour and cloud cover data for this project are obtained from the new Meteosat, also called *Meteosat Second Generation (MSG)*, that is able to provide a much higher spatial and temporal resolution (Figure 5-9).

Improvements in Meteosat resolution	Spatial resolution	Temporal resolution	Spectral channels
Meteosat	2.5 / 5 km	30 min	3
MSG	1 / 3 km	15 min	12

From [Mueller *et al.* 2004:162]

Figure 5-9: *Improved performance of the Meteosat Second Generation (MSG), as compared to Meteosat.*

The authors describe the development of a model (SOLIS - Solar Irradiance Scheme) that uses the spectrally resolved satellite data to model illuminance levels. The illuminance levels predicted by the model are compared to real-sky measurements with satisfactory results (Figure 5-10).



From [Mueller *et al.* 2004:169]

Figure 5-10: *A comparison between measured and modelled illuminance levels, clear-sky conditions, Freiburg, August 2000. The modelled illuminance levels are based on MSG data.*

• **Statistical approach.** Irradiance information may also be obtained from satellite data using a statistical approach, for example as described by Zarzalejo *et al.* [2005]. Similar to the physical approach, the assessment of cloud cover is based on a comparison between clouded and cloud-free images, from which the soft-computing algorithm assesses the cloud cover, learning from its experience and updating its reference base to relevant developments. For the statistical approach, no atmospheric measurements are needed, but, on the other hand, the soft-computing algorithms do need irradiance measurements from the building site in order to make their assessments.

In the context of daylighting, one of the best known methods to assess Meteosat data is Heliosat. A European database of daylight and solar radiation, obtained by this method, is available on the Satel-Light server. It provides information that can be used by architects and other interested parties, free of charge, for daylighting design in buildings [Fontoynont et al 1997; Mueller et al 2004; http://www.satellight.com].

5.2.2 Perception of occupant information

In addition to environmental conditions, an intelligent building envelope is ideally also able to obtain information regarding the needs, preferences and behaviour of the building occupants. Two main types of components are discussed in this section:

- Occupancy sensor
- User-system interface

A user-system interface is a component that enables communication between a control system (in this case the building envelope) and the building occupant. The nature and degree of communication between system and user may vary considerably according to the design of the interface. In some devices, communication is limited to the occupant stating lighting demands in a particular form; others allow the occupant to choose the preferred nature and degree of control over the luminous environment, and provide feedback regarding envelope performance or the consequences of a particular user request. There exist three particular challenges for the communication between user and system, as for communication in general, identified by Shannon & Weaver [1963:4] in *The mathematical theory of communication*:

- **The technical level.** What is the accuracy and speed with which the symbols of communication can be transmitted?
- **The semantic level.** Does the conveyed message make sense, do the symbols manage to convey the precise meaning of the message?
- **The effectiveness level.** Does the message manage to influence the recipient's conduct in the desired way?

There exist many types of user interfaces, each handling these challenges in its own manner, and several examples will be analysed in Section 5.2.2. First, however, occupancy sensors are discussed for the manner in which they obtain information regarding the presence and/or absence of the building occupants.

5.2.2.1 Occupancy sensor

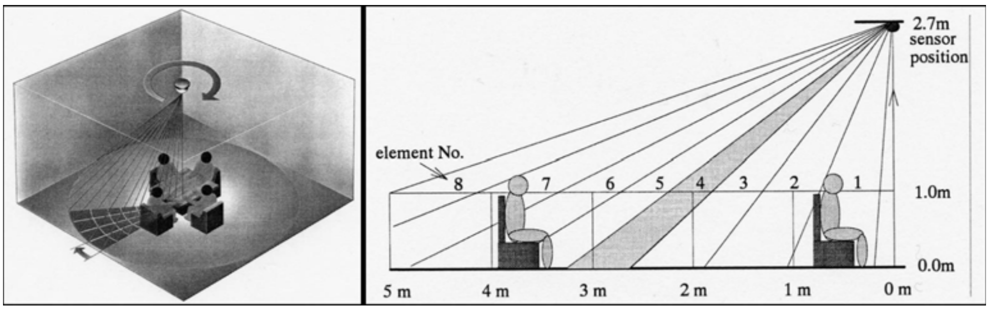
Information regarding occupancy involves several parameters. A first type of data is related to the presence and/or absence of the occupant, but also parameters such as the number of occupants in the room, their position and activity level can be detected.

Two main types of components are discussed in this section: motion sensors and infrared sensors. A third group of components used for occupancy detection consists of applications such as the access card, monitoring the entrance, exit and identity of individual occupants, and the use of equipment and computer networks. An example of this type of identification is the *smart card unit*, discussed in Section 5.2.2.3.

• **Motion sensor.** Motion sensors are used to register the occupant's presence and/ or absence, in order to determine the appropriate balance between occupant comfort and energy strategies. This type of sensors, however, may react to the occupant's apparent absence during periods of inactivity, and discard comfort strategies even though the occupant is still present. In order to avoid this, a certain time delay may be taken into account; this delay time, however, needs to be balanced against the loss of energy savings. One manner in which to handle this dilemma, is the use of an occupancy sensor that adapts its delay time to the individual occupant.

Leephakpreeda [2005], for example, describes the development of an adaptive occupancy sensor that learns the occupant's routines and adjusts its delay times accordingly. To this purpose, the occupant's behaviour is monitored during a few days, allowing the system to learn the variation in the occupant's activity level; this information is then used to determine and update appropriate delay times. Also Garg & Bansal [2000] discuss the development of occupancy sensors that are able to learn occupancy patterns and alter their response time according to factors such as the type of work the occupant is performing, the activity level, and the time of day or year.

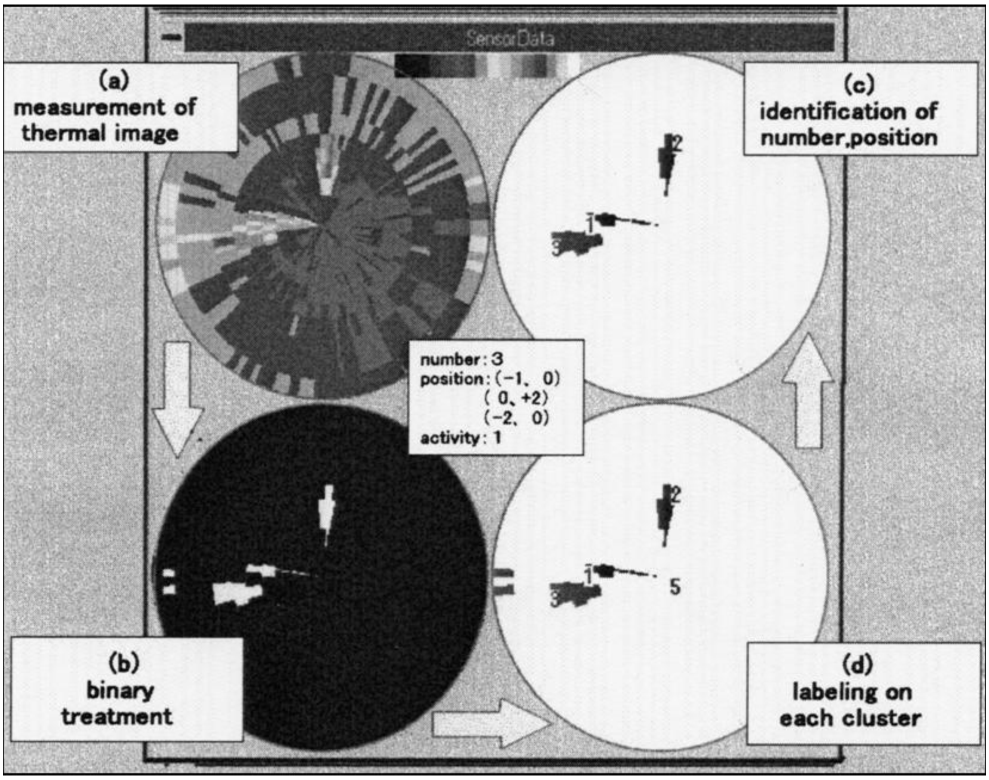
• **Infrared sensor.** Occupant presence can also be detected by means of an infrared sensor that monitors the thermal distribution in the room. The performance of this type of equipment is largely dependent on the width of the sensor's acceptance angle and the corresponding room area that can be monitored. In order to overcome this limitation, a rotary scanning mechanism may be used, an example of which is developed by Yoshiike *et al.* [1999]. The authors describe an occupancy sensor that has a 360^o rotary scanning mechanism that allows the sensor to cover an area of 10 m diameter, as shown in Figure 5-11.



(left) [Yoshiike *et al.* 1999:200]; (right) [Yoshiike *et al.* 1999:202]

Figure 5-11: *An occupancy sensor with 360^o rotary scanning mechanism that allows the sensor to cover the entire room.*

In addition, a fuzzy algorithm allows for an analysis of the thermal images the sensor produces and enables the system to distinguish between *noise* and people. This information makes it possible to assess the number of occupants, their location in the room and their movements (Figure 5-12). In this manner, the authors performed a study where the number of occupants and their locations in a room could be detected with 73 % accuracy in 389 samples (97 % accuracy in case of allowing +/- one person). The sensor used in the research study was able to recognise standing occupants as well as those sitting in front of a desk.



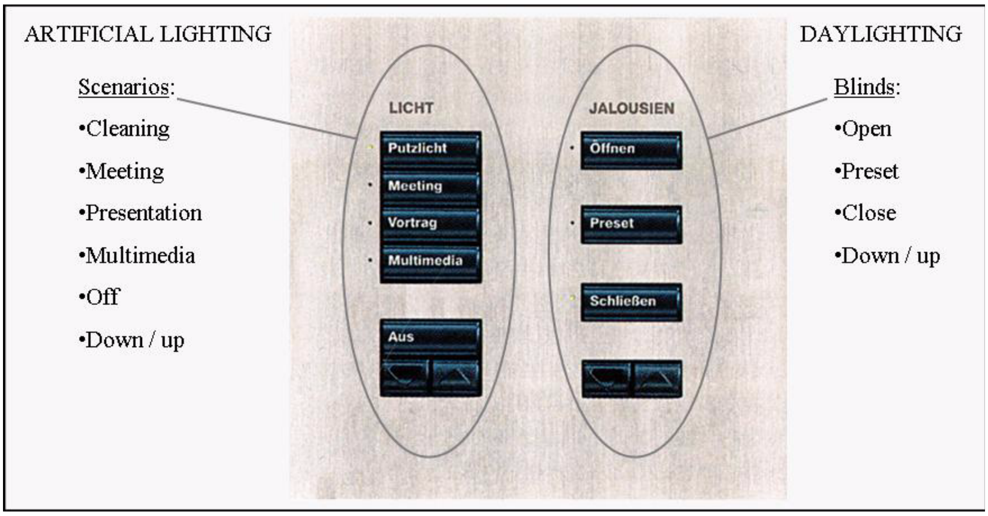
[Yoshiike *et al.* 1999:206]

Figure 5-12: *The presence and position of three persons in a room, as identified from a thermal image by the fuzzy algorithm.*

5.2.2.2 User interface "Seetouchcover" (Lutron Electronics)

A user-system interface, as mentioned earlier, facilitates a certain type and degree of communication between the building occupant and the system (in this case the building envelope). A first type of user interface to be discussed in Section 5.2.2. is *Lutron seetouchcover* by Lutron Electronics, which allows the building occupant to influence natural as well as artificial light levels in the indoor environment. It can be wall-mounted or designed as a hand-held infrared remote control.

With regard to daylighting (Figure 5-13, right), the user interface can be set to operate textile blinds and curtains, either simultaneously or individually. The user may adjust the position of the blinds and curtains randomly or according to a preset preference. A timer mechanism can also be applied to lower the blinds to the desired position according to the time of day.



From [IntelligenteArchitektur **50**:10]

Figure 5-13: *The Lutron* seetouchcover *user interface.*

As part of an intelligent building envelope, this type of user interface does not allow occupants to define their indoor luminous work environment directly. It does, however, give them the opportunity to influence the *control state* of that environment, i.e., the extent to which the envelope admits daylight indoors. The occupant is given a choice related to the portion of the aperture that is to be covered by textile blinds or curtains; options related to the particular transmission characteristics of the cover, such as Venetian blinds with a variable slat angle, are not available.

With regard to the nature and timing of the requested adjustment, the occupant has full control. When using the interface, the occupant signals dissatisfaction with current daylighting conditions, however, no information regarding the source of dissatisfaction is revealed: the occupant may want to adjust the blinds due to a diversity of reasons such as glare, privacy, and direct sun. This makes it difficult for an intelligent building envelope to suggest an alternative course of action, with better overall consequences for daylighting quality. Overruling the occupant's request would, in addition, cause irritation.

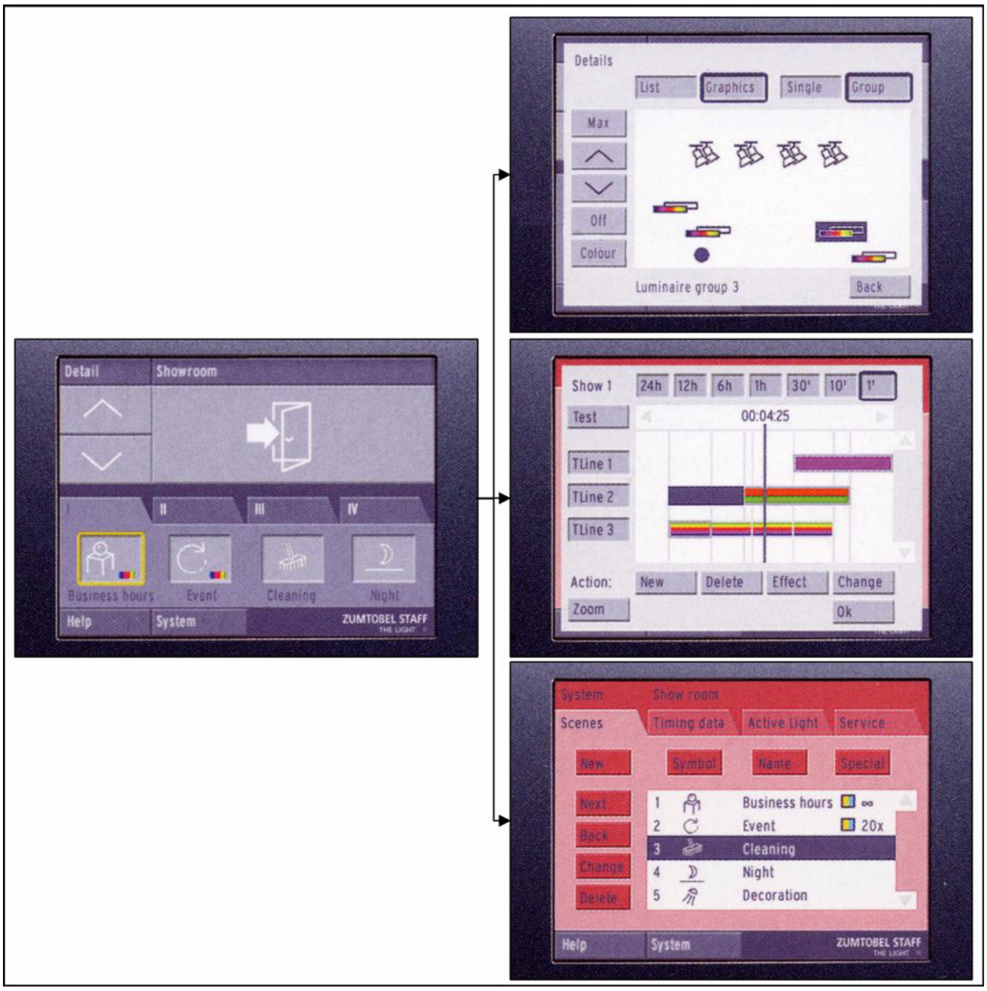
In addition to daylighting, this type of user interface also includes control of the artificial lighting output (Figure 5-13, left), which can be adjusted upwards or downwards. It is also possible for the occupant to predefine artificial lighting scenarios according to, for example, the type of task to be performed in the room.

This type of user interface does not provide a combination of artificial and daylighting strategies, where the building occupant's requests are first attempted served by means of natural light sources. A step in this direction is made in the *TEmotion* user interface, presented in Section 5.2.2.4.

5.2.2.3 User interface "Emotion Touch Panel" (Luxmate / Zumtobel Staff)

A second type of user interface is a control panel that displays information in a hierarchical manner, such as the *Emotion Touch Panel* designed by Luxmate and Zumtobel Staff in collaboration with Matteo Thun. The touch panel is designed to be used in co-operation with an *Active Light* system that adjusts the intensity, directionality and colour of artificial lighting to the user's individual requests. The *Active Light* system, based on *DALI* technology (Digital Addressable Lighting Interface), is described in further detail in Section 5.4.1.3.

The user interface enables the building occupant to communicate needs and preferences to the control system. In basic mode, the touch panel shows only the most general functions; more detailed information is provided when requested. The main screen allows for adjustments in lighting intensity, by means of arrows; it is also possible to choose particular lighting scenes. For more advanced settings, the user can open more detailed screens and configure the system according to individual preferences (Figure 5-14). The control system also displays performance errors such as lamp failure, and incorporates emergency lighting.



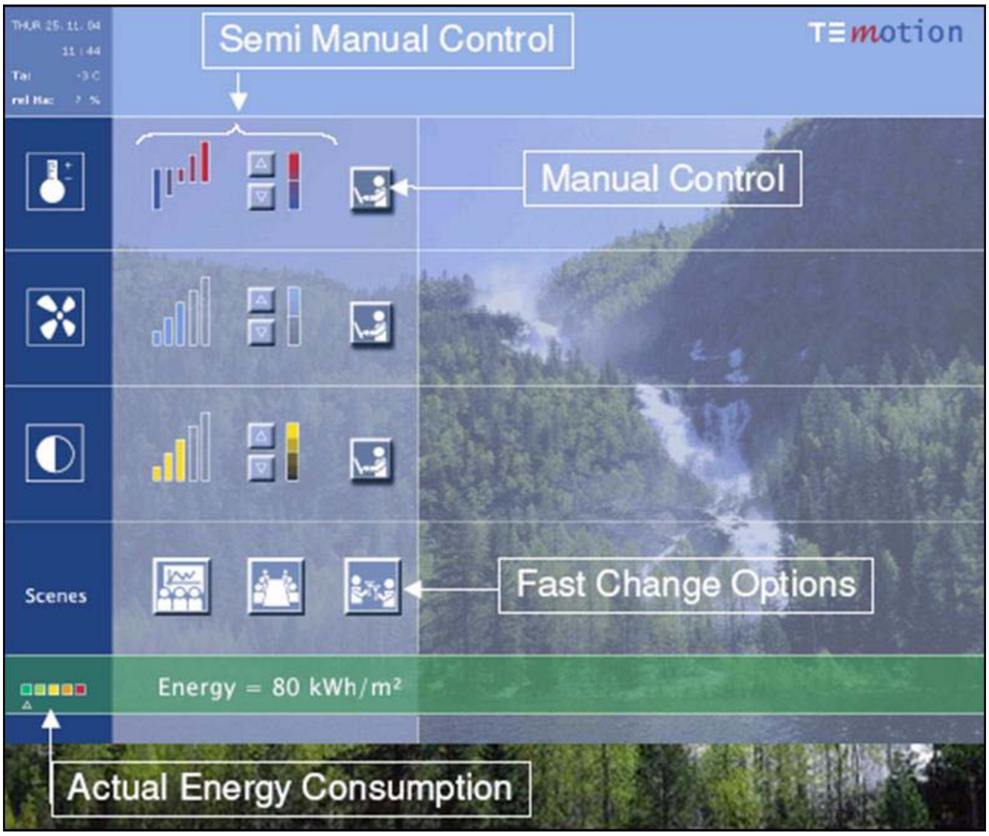
Provided by [Zumtobel Staff / Luxmate]

Figure 5-14: *The Emotion touch panel; (left) main screen; (right) secondary screens for more detailed configuration.*

The control system can be incorporated into a more comprehensive building management system, and co-ordinated with, amongst others, shading system and presence detectors, and various sensors for outdoor lighting conditions. Incorporated into an intelligent building envelope, the occupant's detailed configuration of luminous settings can help the envelope to optimise its artificial and daylighting strategies according to the performance of particular tasks, the type of weather, and the human circadian rhythm. The system as described here collaborates with artificial lighting alone, but this could be extended to include daylighting as well.

5.2.2.4 User interface "TEmotion" (Wicona / Hydro Building Systems)

A third example of a user interface is integrated in the *TEmotion* facade concept with integrated artificial lighting, developed by Wicona / Hydro Building Systems. This facade concept is to be discussed in Section 5.4.3.2. Similar to the previous example, this user interface features a hierarchical structure where the building occupant is free to choose the preferred level of detail in configuration. In this case, however, the functionality of the user interface is extended to include artificial as well as daylighting strategies. In addition, the user interface allows the occupant to state the preferred form of control for heating and cooling, and provides the occupant with feedback on how occupant requests influence the facade's energy performance.



Provided by [Hydro Building Systems]

Figure 5-15: *The TEmotion user interface.*

In addition, the symbols used for communication between the user and the envelope are given particular attention. With this user interface, the building occupant has the opportunity to express lighting needs and preferences in various forms, increasing the chance of successfully conveying information to the control system.

In semi-manual control mode, the occupant can adjust the indoor luminous environment by stating preferences for ‘more’ or ‘less’ light, or by choosing a particular light setting customised for the performance of a specific task or function in the room. The control system or building envelope then evaluates whether this request can be fulfilled with the available daylight sources, or whether additional artificial lighting is needed. In addition, the control system chooses the appropriate ratio between fluorescent lighting and LED, based on the time of day and the intensity of natural light [private communication with Dietmar Brüderl, Hydro Building Systems; detailed documentation not available to the public].

In manual control mode, the occupant is allowed to influence the control state of Venetian blinds and artificial lighting, and a variety of icons is available to facilitate this operation. The slat angle of the Venetian blinds can be changed by means of arrows; the upper and lower part of the blinds are to be adjusted separately. A similar control function is available for the intensity of the artificial lighting, as well as for its colour appearance. For the colour appearance, the occupant has a choice between fluorescent lighting and light-emitting diodes (LED); the latter provides ‘blue light’ if the occupant so desires [*ibid.*].

It is further interesting to note the variety of icons applied in the user interface. While the Venetian blinds are depicted by a drawing of upper and lower blinds, respectively, the control of fluorescent lighting features a drawing of an incandescent light bulb, and the control of the LEDs is indicated in actual writing.

The user interface also provides feedback on the influence of the occupant’s choices on the energy performance of the facade. Theoretically, such information may persuade the occupant to choose ‘correctly’. In practice, however, there is no guarantee for a beneficent influence; as explained in the introduction to Section 5.2, the communication between the envelope and the occupant may encounter challenges on different levels. The information regarding the facade’s energy performance described in kWh/m^2 is accurate, but does not necessarily make sense to the building occupant. The colour scale, on the other hand, ranging from green (positive) to red (danger zone), may be easier for the occupant to relate to. However, even when the message of energy performance is conveyed to the occupant, there is no guarantee that the information will influence the occupant’s choices in the desired manner.

5.3 The implementation of reasoning

This section covers physical applications that can be implemented in an intelligent building envelope to facilitate the following reasoning processes (Figure 5-16):

- Processing information from multiple sources into an optimal solution
- Anticipating environmental conditions
- Learning occupant preferences
- Anticipating the outcome of envelope actions

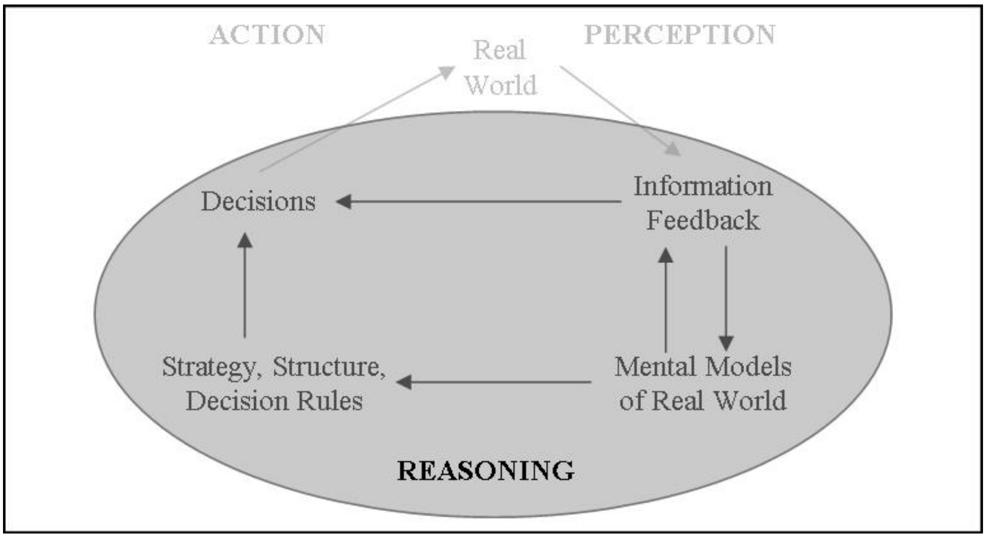


Figure 5-16: *Reasoning processes help an intelligent building envelope elaborate an appropriate response to changes in its environment.*

As mentioned in Chapter 2, the reasoning skills described above need to be supported by a specific type of information technology; *soft computing*, inspired by processes related to human intelligence, can help an intelligent building envelope to obtain the adaptation and operation time that is required in its interaction with the environment.

In Section 5.3, the characteristic weaknesses and strengths of this type of technologies are discussed, along with a selection of their applications in daylighting quality:

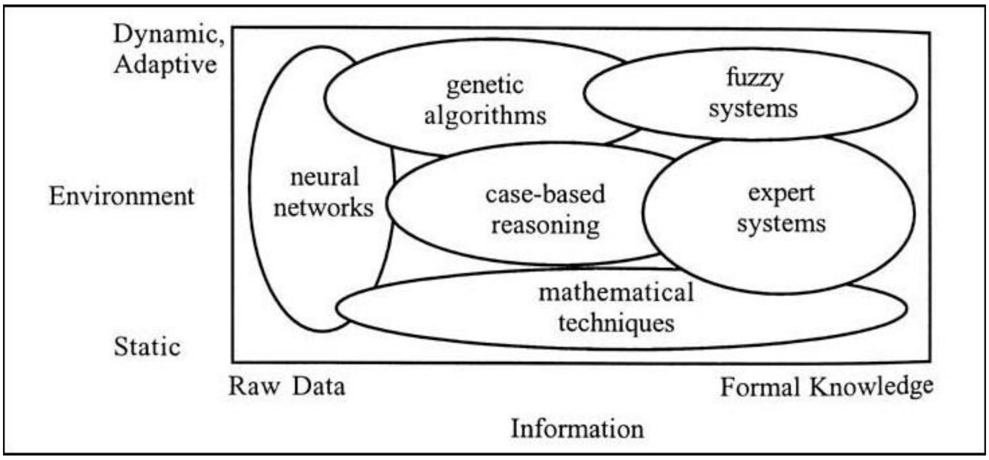
- Soft computing technologies
- Applications for daylighting quality

5.3.1 Soft computing technologies

Section 5.3.1 contains a short review of the following soft computing technologies:

- Expert systems
- Artificial neural networks
- Fuzzy systems
- Evolutionary algorithms
- Case-based reasoning

These technologies can be used as stand-alone systems, or, due to their complementary nature, combined with each other into *hybrid systems* that mitigate the weaknesses of each of the systems and enhance their strengths.Such hybrid systems may consist of loosely-coupled modules, where each element of the task at hand is addressed by the most appropriate technology; alternatively, they can be used in a sequential manner, or even appear as an integrated structure with fundamentally new characteristics [Medsker 1995]. Figure 5-17 presents an overview of the different technologies to be discussed, along with their main characteristics.



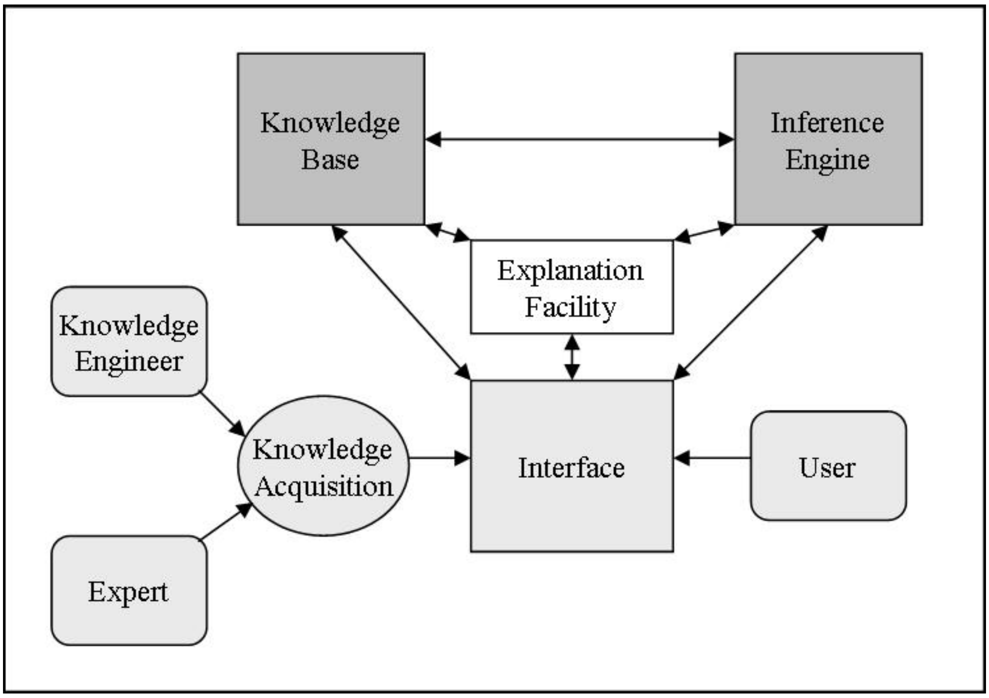
[Medsker 1995:224]

Figure 5-17: *An overview of soft computing technologies.*

5.3.1.1 Expert systems

Expert systems (ES) or *knowledge-based systems* simulate human expertise within a specific domain, and usually consist of two main elements (Figure 5-18):

- Knowledge base
- Inference mechanism



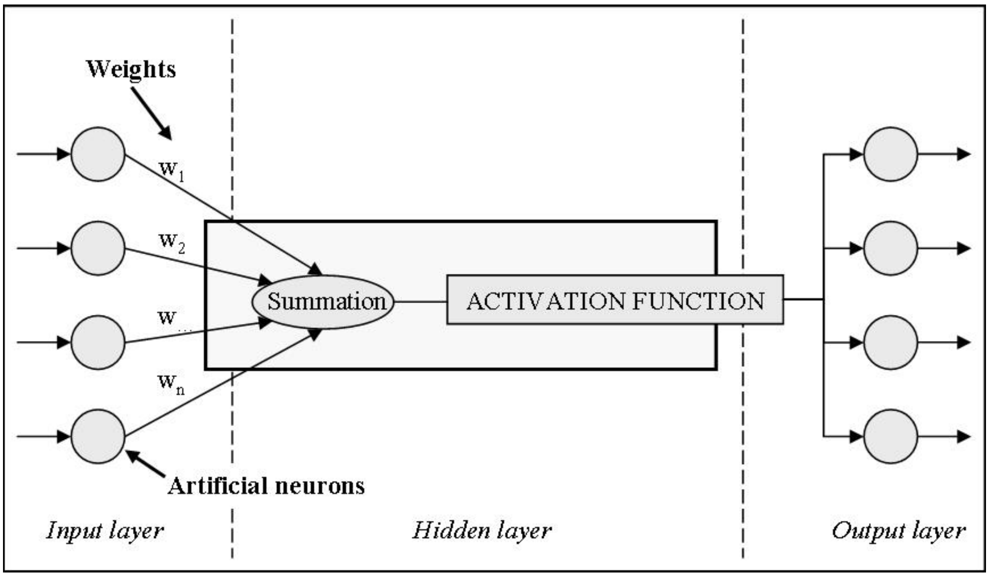
From [Medsker 1995:3]

Figure 5-18: *The typical structure of an expert system, with a knowledge base and an inference mechanism.*

The *knowledge base* contains domain knowledge of human experts, supplied with published information and experimental findings. The *inference mechanism* manipulates the stored knowledge in order to work out appropriate response strategies [Garg 2001]. The important advantage of having an architecture that separates the knowledge base from the inference mechanism is the ease of updating the knowledge base without interfering with the inference mechanism [Medsker 1995].

5.3.1.2 Artificial neural networks

An *artificial neural network* (ANN) is a computational model of the human brain. The model is composed of an input layer, a number of hidden layers, and an output layer (Figure 5-19).



From [Kalogirou 1999:1076, 1077]

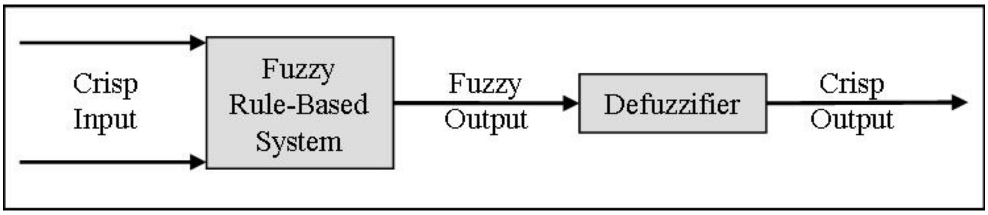
Figure 5-19: *A simplified model of an artificial neural network.*

An ANN is composed of a group of interconnected, interacting artificial neurons, which can be trained to produce a desired output on the basis of a given input and data regarding the past performance of the system. During the training, the weights of the connections between the neurons are adjusted in order to create the appropriate relationship between input and output. After training, these weights can be used to adapt the system to new conditions in the environment [Kalogirou 1999].

Storing knowledge as connection weights rather than as explicit rules, along with the ability to learn from data sets, enables an ANN to handle incomplete and vague information that would cause humans to make decisions on an intuitive basis. In addition, these characteristics make it possible for an ANN to detect information patterns, distinguish between relevant and superfluous data, and even predict future developments in parameters such as energy load and weather conditions. Tasks requiring high accuracy and precision, however, can not be handled effectively by an ANN [Guillemin & Morel 2001; Kalogirou 1999].

5.3.1.3 Fuzzy systems

Fuzzy systems (FS) combine approximate reasoning with an expert knowledge base, and are, similar to ANNs, inspired by human intuition. Based on a human rule-of-thumb approach, the approximate reasoning technique reduces complex systems to easy-to-understand rules (Figure 5-20). This enables the expert knowledge base to be used also when incomplete or vague information from the environment needs to be handled, or new situations occur [Garg 2001].



From [Medsker 1995:9]

Figure 5-20: *The process of a fuzzy rule-based system.*

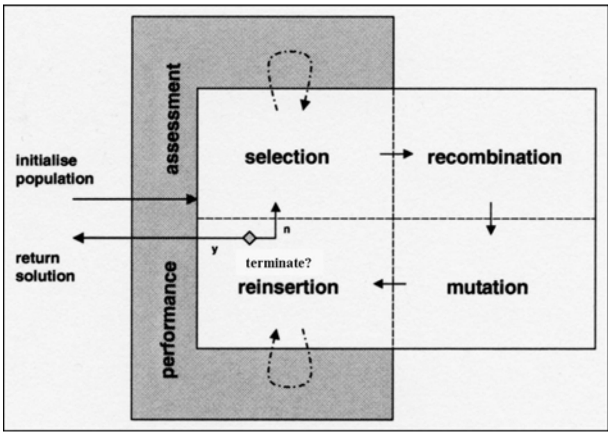
This technique is well suited to deal with imprecise input from the user, such as a request for 'rather bright' lighting conditions. In addition, the system is able to give feedback in similar terms, which may help the communication between user and machine [Chin & Qi 1998; Medsker 1995].

The severe weakness of fuzzy systems is the trial-and-error method by which they determine and tune their parameters; this requires a lot of iteration, particularly when the number of parameters and rules increases significantly [Hagras *et al.* 2003].

5.3.1.4 Evolutionary algorithms

Evolutionary algorithms (EA) are inspired by biological evolution, and more specifically by the principles of natural selection and population genetics. In order to create desirable solutions to a problem, a population of potential solutions is evolved over several generations by means of recombination and mutation (Figure 5-21).

Each of the potential solutions has a genetic code that consists of a number of design parameters relevant to the problem. As the parameter sets are encoded, several types of variables may be represented within a single solution. Starting off with random values, potentially combined with some known good solutions, these genetic codes are then recombined and mutated into solutions that are more fit to solve the problem at hand. The better a solution performs at solving the problem, the higher its chances are of propagating its genes to the next generation [Fleming & Purshouse 2002].



From [Fleming & Purshouse 2002:1224]

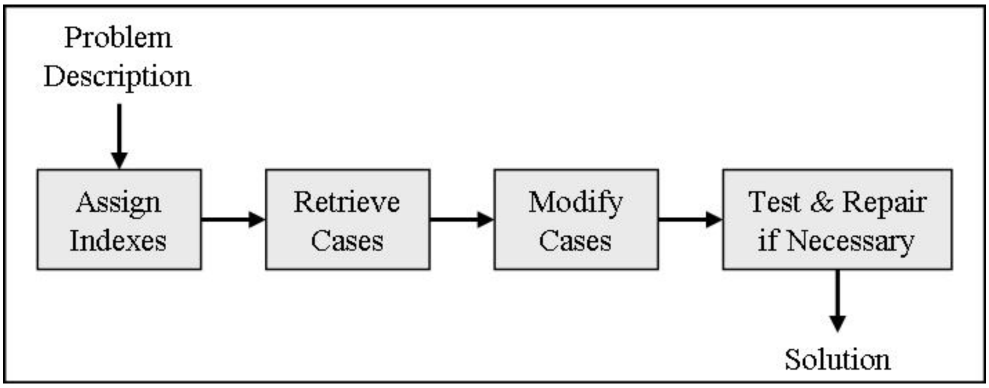
Figure 5-21: *A simplified model of an evolutionary algorithm, based on principles of natural selection and population genetics.*

Evolutionary algorithms are able to simultaneously support several solutions to a problem, and can thus point out possible trade-offs. This makes them very well suited for decision support and multi-objective optimisation. In addition, EAs feature a directed-search mechanism that makes them very effective in comparison to a totally random or enumerative search. An EA can, for example, be used in the fault diagnosis of components, where it is able to detect, isolate and identify the fault. EAs can also be designed to optimise the placement of control components and sensors, or to incorporate specific building constraints, either by presenting them as objectives to be met, or by assigning a low fitness value to infeasible solutions [Fleming & Purshouse 2002].

Unfortunately, EAs are very computationally intensive, which hinders their application in online, real-time control or safety-critical systems. The future availability of more powerful computer systems should ameliorate this condition [Fleming & Purshouse 2002; Hagras *et al.* 2003].

5.3.1.5 Case-based reasoning

Case-based reasoning (CBR) solves a problem situation by referring to past experience. Whenever a problem is encountered, previously gained and stored experience on comparable cases is retrieved from the knowledge base, and adapted to the current situation (Figure 5-22).



From [Medsker 1995:11]

Figure 5-22: *A typical case-based reasoning process for finding solutions to a problem.*

Therefore, case-based reasoning is most usefully applied when plenty of information on past experiences is available. If no relevant case can be found, human intervention is needed to extend the knowledge base.

CBR can be used as an alternative to expert systems; it has the additional advantage of being able to accumulate knowledge by experience and, thus, to learn and improve over time, while expert systems always start from the same ground level [Medsker 1995].

Case-based reasoning can also be applied in prediction tasks in a broad range of situations. However, the CBR process lacks transparency as it does not offer an explanatory justification for its predictions, which adds a degree of uncertainty [Hayes-Roth 1995].

5.3.1.6 Hybrid systems

The soft computing techniques described above are often combined with each other to fully exploit each of their skills while mitigating their weaknesses. In the following paragraphs, it is described how the performance of one particular technique can be enhanced by coupling it to or integrating it with others.

- **Expert systems**
  • Combined with *artificial neural networks*, expert systems integrate expert knowledge with training by means of data sets, which makes them able to simulate human decision making in case of incomplete information.

• Combined with *fuzzy systems*, expert systems are able to handle uncertain and imprecise data that appear in practical problems, such as feedback from and to the user and knowledge acquired from experts.
• *Evolutionary algorithms* can be used to make expert systems less time-consuming by means of their ability to clarify trade-offs among conflicting factors and to deduct decision rules in large quantities of data. In addition, they can dynamically adapt the expert rule base to changing conditions in the environment.
• *Case-based reasoning* can be used to improve the performance of expert systems as well. CBR and ES both solve problems by means of a knowledge base; CBR, however, easily acquires new knowledge, whereas an ES always starts from the same ground level unless the knowledge base is updated externally. This external update can be performed by CBR [Medsker 1995].

- **Artificial neural networks**
  • The combination with *fuzzy systems* increases the learning performance of the artificial neural network; the use of a FS enables an ANN, for example, to receive and process incomplete and vague data.
  • The learning performance of ANNs can also be improved by means of *evolutionary algorithms*. EAs feature a directed search mechanism, which can be used to pre-process data sets and incorporate some solutions with good parameters, before presenting the data to an ANN; this enables the ANN to find optimal solutions faster [Medsker 1995].
  • In addition, artificial neural networks may be coupled with *expert systems* as described in the previous paragraph.

- **Fuzzy systems**
  • The performance of fuzzy systems can be enhanced by combining them with *evolutionary algorithms*. Fuzzy systems and evolutionary algorithms both perform well in terms of efficiency and execution speed. Fuzzy systems are, in addition, able to represent expert knowledge in a transparent manner; however, this skill is reduced with increasing complexity and size of the system to be represented. Evolutionary algorithms, on the other hand, can effectively represent high degrees of complexity due to their directed-search mechanism and the ability to support several solutions simultaneously, and this makes evolutionary algorithms a powerful tool to select high-performance parameters for fuzzy systems. EAs also include random elements, which help avoid the system from getting trapped in local minima. In addition, EAs are able to learn fuzzy rules, adapt them to changes in the environment, and eliminate all rules that do not significantly contribute to the system. This makes them specifically suitable for adaptation in direct, i.e., on-line and real-time interaction with a changing environment [Chin & Qi 1998; Hagras *et al.* 2003; Medsker 1995].

• In addition, fuzzy systems may be coupled with *expert systems* and *artificial neural networks* as described in the previous paragraphs.

- **Evolutionary algorithms**
  • *Expert systems* can be used to optimise the search parameters evolutionary algorithms use, by adding expert knowledge.
  • Combined with *fuzzy systems*, evolutionary algorithms are able to dynamically control their search parameters [Medsker 1995].
  • In addition, evolutionary algorithms may be coupled with *expert systems*, *artificial neural networks* and *fuzzy systems* as described in the previous paragraphs.

- **Case-based reasoning**
  • Case-based reasoning solves problems by applying information from a knowledge base, which is continuously updated with new experiences. Combining CBR with *evolutionary algorithms* or *artificial neural networks* can improve the case retrieval process and find more relevant cases in a shorter amount of time.
  • When the rule base is stable, also *expert systems* can be used to improve CBR's retrieval and adaptation processes. In addition, case-based reasoning may be coupled with *expert systems* as described earlier.
  • *Fuzzy systems* can simplify user input and consultation of data by allowing the use of natural language [Medsker 1995].

5.3.2 Soft computing applications for daylighting quality

The overview of soft computing technologies, and particularly of the hybrid systems, shows a promising development towards flexible systems that can learn and adapt themselves in direct interaction with the environment. It is warranted, however, not to have blind faith in soft computing technologies, as "*intelligent systems only perform as well as their representations of the task they are trying to perform and of the world they are trying to perform it in. If these representations are reasonable, then even extremely simple algorithms can result in useful performance. If they aren't then no algorithm, no matter how sophisticated, can yield good performance*" [Birnbaum *et al.* 1997:173].

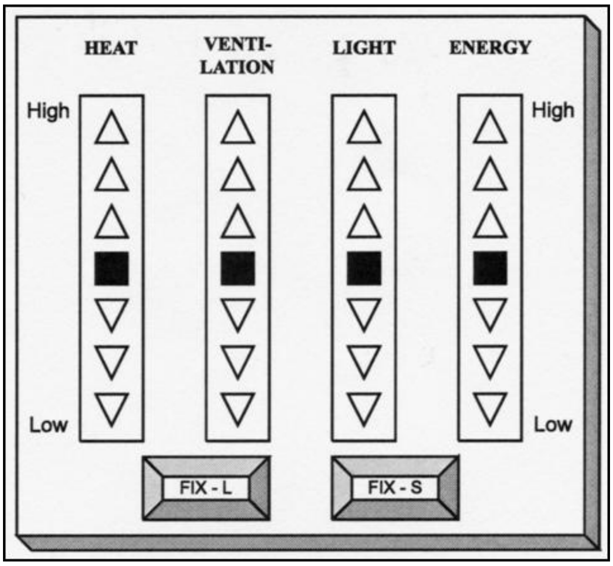
Soft computing algorithms are used to execute a wide range of functions, and research is providing them with a steadily increasing degree of performance. Some of these applications were already discussed in Section 5.2 on perception, where the algorithms were used to enhance the retrieval of information on the environment and the building occupant. Section 5.3.2 focuses on the reasoning processes that have been developed and applied in several physical applications in close co-operation with the particular task to be performed, and the environment it is to be performed in.

5.3.2.1 Smart card unit

The *smart card unit* is a component that combines a user-system interface with occupancy detection, and is able to register and learn occupant preferences. Communication between user and system occurs in two directions; the user can use the interface to convey needs and preferences regarding heating, ventilation and lighting, while the system conveys information regarding its own performance, for example related to energy use. The system is developed by Kolokotsa *et al.* [2002a; 2002b; 2005]. The front panel of the unit is depicted in Figure 5-23.

An evolutionary algorithm is used to find a suitable response to the user's requests; thermal, visual and indoor air quality parameters are optimised to occupant requirements with a minimum of energy resources and a preference for so-called *passive* techniques. The output of the evolutionary algorithm is then fed to a fuzzy controller that controls the indoor climate parameters accordingly. With regard to the luminous environment, the following equipment is taken into account:

- Photosensors, for information regarding illuminance levels in lux.
- Venetian blinds, for shading purposes, not for the redirection of light
- Artificial lighting, for zoning and dimming strategies



[Kolokotsa *et al.* 2002a:122]

Figure 5-23: *The front panel of the smart card unit.*

Each building occupant has a smart card at her disposal, where individual needs and preferences are stored and updated over time. When the card is inserted in the card unit, the occupant's presence is registered and the individual settings for the control parameters detected, upon which the control system will aim to reach those values.

The user can express specific requirements by means of arrows requesting a higher or lower value of a particular parameter; these requests are then processed by a fuzzy algorithm (a process described on the next page). No numbers are given, as it was assumed by Kolokotsa *et al.* [2002a:122] that *"users are not usually able to 'understand' the relation between the control variables values and their personal comfort needs."* In addition, there are extra on/off options for lighting and shading, which can be used in specific functions such as presentations.

In order to update the values for the control parameters over time, the card has a short-term and a long-term memory. Originally, the card only has default values stored. Each time the user requests a change by means of the control panel, this request is sent to a central computer, along with the current settings. The central computer evaluates and updates the settings, and the values in the card's short-term memory are updated accordingly.

In order to update the long-term memory, the short term requirements are evaluated over a specific period of time, for example one week, during which the card learns more about the preferences of the individual user, and this information is then stored into the card's long-term memory. Regular updates of the long-term memory are intended to minimise the communication necessary between occupant and system, as the system knows the occupant preferences and controls the indoor climate accordingly. In this manner, the system can provide the occupant with a feeling of control, while minimising the occupant's need to physically exercise control.

When the occupant makes a request, the control unit not only registers the specific request made, but also interprets the user's behaviour. Kolokotsa *et al.* [2002b] argue that when occupants want a significant alteration of current conditions, they often request a much larger change than actually desired, and the control system thus needs to mitigate the occupant's request in order to avoid overshoot. When small changes are requested, on the other hand, the control system needs to react accurately and quickly; a similar response is needed when the occupant makes frequent requests. This practice, the authors argue, enables the system to respond to the user's requests in a more appropriate manner.

The control unit has been installed in the Electronics Laboratory of the Technical University of Crete, where system response is tested in real-time operation. The system uses a hierarchical control structure; comfort parameters can be set on a local level, for each room or each occupant, while the energy consumption is managed more centrally, taking into account each of the local comfort conditions. Communication between the different components occurs via a local operating network (LON), which makes it possible to integrate this system in new as well as in existing buildings.

Kolokotsa *et al.* [2005] report a reduction of 20 % in energy consumption for heating and cooling, and 38 % for lighting on an annual basis, compared to a situation without control system. In addition, user surveys have been performed to detect occasional dissatisfaction with the control operations of the system.

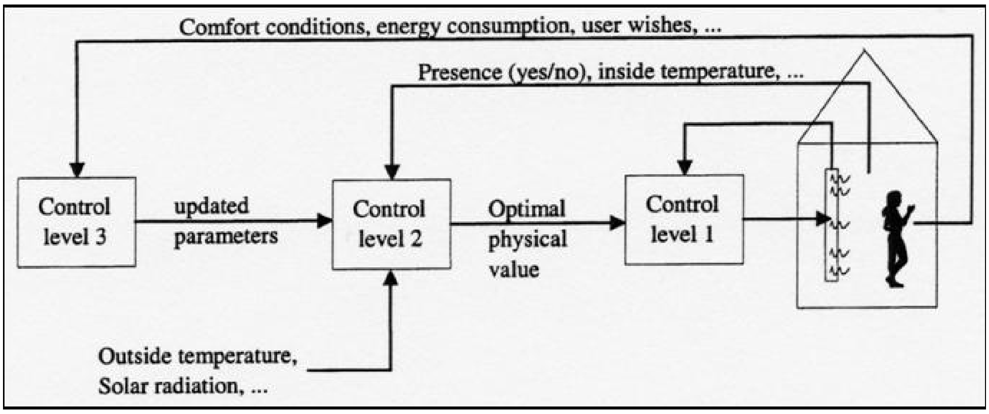
5.3.2.2 Self-adaptive lighting controller with wish filter

Another example is a *lighting controller* integrating artificial and daylighting strategies into a more comprehensive building management system with heating and ventilation control. This lighting controller has been developed at the *Laboratoire d'Energie Solaire et de Physique du Bâtiment* (LESO-PB) in Lausanne, Switzerland, as part of the EDIFICIO (Efficient Design Incorporating Fundamental Improvemetns for Control and Integrated Optimisation) research project. The controller is described, amongst others, by Guillemin & Molteni [2002] and Guillemin & Morel [2001; 2002].

The natural lighting strategies in this project consist of control of shading devices for glare and illuminance levels (in the presence of the user) and for solar heat gain (in the absence of the user). Additionally, artificial lighting is used strictly as a supplement to the available daylight, in order to increase illuminance levels according to user requirements. The control algorithms used for artificial and daylighting strategies are self-adaptive due to the use of fuzzy systems and evolutionary algorithms.

Three levels of control are identified (Figure 5-24):

- *Level 1* controls lighting and shading devices according to the output of level 2.
- *Level 2* registers the state of environmental and occupant parameters, and uses an expert-fuzzy system to elaborate an appropriate response.
- *Level 3* manages the long-term strategies of the controller, and uses evolutionary algorithms to update the algorithms in level 2 accordingly.



[Guillemin & Morel 2001:478]

Figure 5-24: *The lighting controller uses three distinct levels of control.*

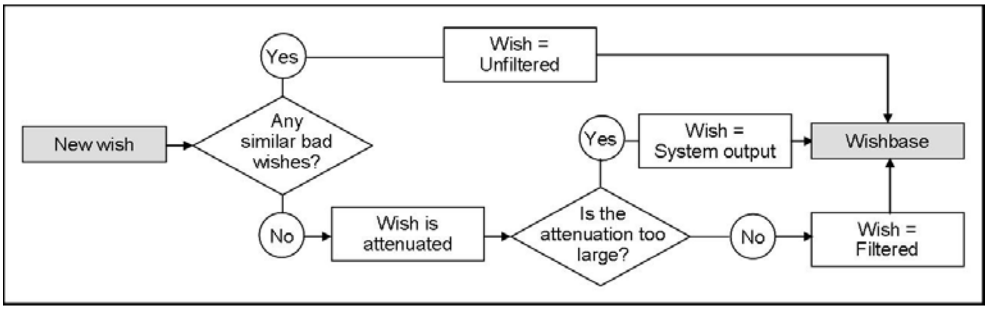
The operation of the lighting controller is subdivided into several functions, among which are a shading device controller, an artificial lighting controller, a user wish filter, and a climate predictor.

• **Shading device controller.** This controller handles textile as well as Venetian blinds. In the presence of the user, the blinds are controlled to block direct sun and to provide the illuminance levels requested by the user; in addition, a blind filter reduces the movements of the blinds so as to avoid irritating the user. The shading device controller uses a fuzzy system that assesses the following data:

- *Vertical illuminance on the facade* (global and direct), combined with the blind angle, is used to assess glare and calculate the inside horizontal illuminance. The blind angle, in this context, is important not only for the visibility of direct sun, but also for the brightness contrasts the slats themselves might create when their bright reflections occur in the occupant's visual field.
- *Season*, a parameter that enables the controller to consider the desirability of parameters such as solar heat gain and night-time insulation, and improve its energy efficiency by optimising the long-term use of passive solar gains.
- *Solar azimuth and height*, enabling the controller to differentiate its strategies not only according to solar incidence angle, but also according to the particular surfaces in the occupant's visual field that are irradiated.
- *Brightness ratios*. Using three luxmeters in the room (one horizontal and two wall illuminance levels) an algorithm is suggested to calculate brightness ratios and the corresponding glare risk. This algorithm, however, is not tested.

• **Artificial lighting controller.** This controller increases indoor illuminance levels up to the illuminance setpoint required by the user. The age of the lamps as well as the accumulation of dust are taken into account, and the artificial lighting output adjusted accordingly; these parameters are updated every night.

• **Wish filter.** The users can forward their requests by means of a keyboard, aiming to alter the artificial lighting output, the blind angle or position, and the temperature setpoint. In the first stage of the project, the user's wishes were only included in the system's short-term memory, and discarded after a period of typically one hour, leading to considerable occupant frustration. Therefore, a wish filter (Figure 5-25) has been developed on the basis of evolutionary algorithms, permitting the system to learn the user's wishes while simultaneously attempting to attenuate energetically inappropriate requests; nevertheless, when energetically bad wishes are repeated by the user, the controller accepts them anyway. In practice, the parameters are not updated in real-time but during the night; when the user expresses a particular wish during the day, this wish is granted and the automatic controls shut down in order to not intervene with the request. This delay prevents user irration, but does not lead to optimal energy efficiency [Guillemin & Molteni 2002].



From [Guillemin & Molteni 2002:1093]

Figure 5-25: *The principle of the wish filter.*

• **Climate predictor.** This algorithm is based on artificial neural networks. Taking into account the outside temperature and the horizontal global solar irradiance for different points in the past time, new values are predicted for the near future and the system's long-term strategies adjusted accordingly; the predicted values are updated weekly. This function is particularly useful for the optimised use of passive solar energy gains.

The energy performance of the integrated lighting and heating controller is tested in full-scale in an occupied office building. The results show a reduction of 7 % (mid-season) to 18 % (summer) and 40 % (winter) of the total energy consumption as compared to a conventional system (no automatic blind controol, no automatic artificial lighting control, proportional heating controller with saturation). This favourable result is partially due to the night-time reduction of heating power in anticipation of solar heat gains the next day [Guillemin & Morel 2001].

Additional advantages, according to the authors, are the ease with which the lighting controller is adjusted to any kind of actuator or controller device, and the self-adaptive algorithms that ensure a simplified commissioning. In a long-term perspective, the system is able to learn and adapt to the individual occupant's wishes, adjusting the indoor climate to the individual occupant without the latter having to exercise control.

5.3.2.3 Online learning, adaptation and control

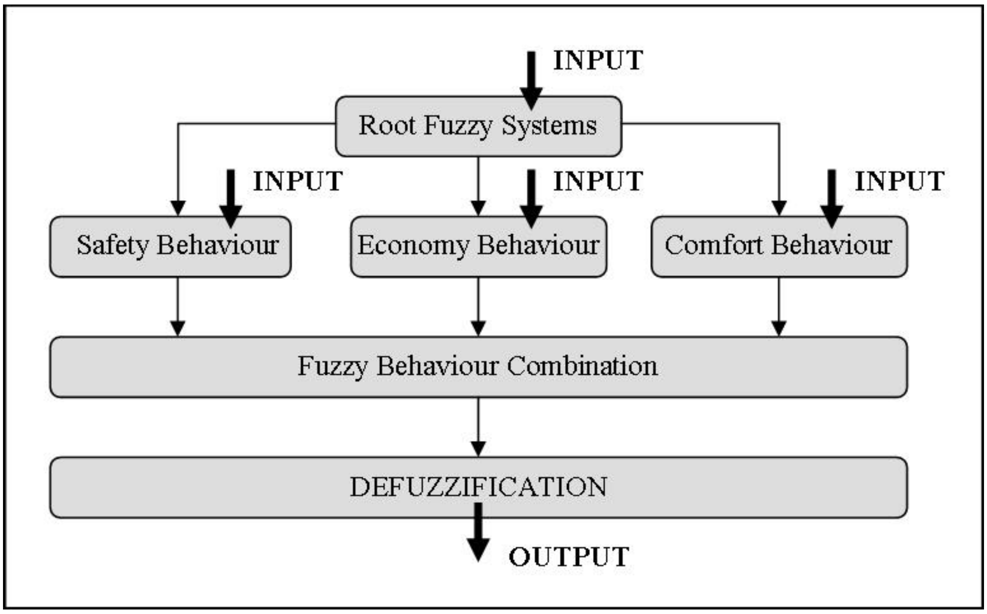
While in the previous example, the learning of occupant wishes occurred offline during the night, Hagras *et al.* [2003] describe a control system based on fuzzy systems and evolutionary algorithms that is able to learn and adapt to occupant behaviour online (in direct interaction with the user) and in real-time (without notable delay). Several strategies have been combined to achieve this complicated control process:

- Combination of fuzzy systems & evolutionary algorithms
- Decomposition into multiple behaviours (see also Chapter 2)
- Direct interaction with the occupant

• **Combination of fuzzy systems & evolutionary algorithms.** The system determines the user needs based on sensors and a user interface, rather than relying on pre-programmed models. The direct interaction between user and controller is possible due to the combined use of fuzzy systems and evolutionary algorithms. Fuzzy systems are able to handle the user's imprecise requests, however, they use a technique of trial-and-error to elaborate an appropriate response. This procedure would in real-time take too much time and cause a considerable delay in system response to the user's request. A combination with evolutionary algorithms, though, is able to reduce this trial-and-error process considerably.

• **Decomposition into multiple behaviours.** In order to simplify the overview of all factors to be taken into account, several behaviours have been identified, each corresponding to a particular problem that needs to be managed, such as safety, economy or comfort (Figure 5-26). Each of these modules optimises its own parameters, after which the recommendations of all of the modules are merged into one. The optimisation of each module as well as the co-operation among them is managed by means of fuzzy systems. The purpose of each of the behaviours was already explained in Chapter 2. As input data, the system uses the following parameters, along with occupancy data retrieved in direct interaction with the user:

- Outside ambient temperature
- Room temperature
- Outside illumination level
- Inside illumination level



From [Hagras *et al.* 2003:38]

Figure 5-26: *The fuzzy control system, decomposed into multiple behaviours.*

- **Direct interaction with the occupant.** In order for the control system to learn and adapt online and in real-time to the occupant's requests, an approach based on evolutionary algorithms has been developed. When the user interacts with the system and requests a change, the system attempts first to apply the most suitable response it finds in its memory. If the result is not satisfactory, the system starts an optimisation process with the use of evolutionary algorithms, beginning from the solution previously found to be most suitable, and elaborating a new, better response. In this manner, the system can learn new rules that are more suitable for the individual occupant, and delete the rules that are, in a long-term perspective, found to be inappropriate. According to the authors, this procedure takes only three minutes, as the combination of fuzzy systems and evolutionary algorithms requires a limited number of iterations.

5.4 The implementation of action

The material use, form and composition of envelope components determine to a large degree how an intelligent building envelope is able to act upon changes in its environment.

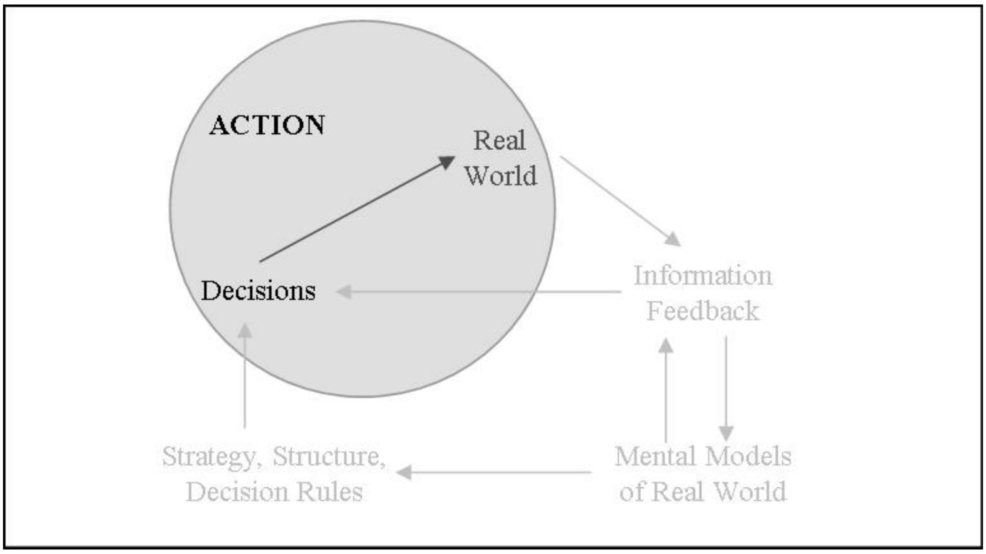


Figure 5-27: *Having elaborated an appropriate strategy in response to changes in its environment, an intelligent building envelope needs materials and components to execute this response into the real world.*

Section 5.4 presents a selection of materials and components that may be used to execute the responses elaborated by the reasoning system. The components are organised into three main groups, according to the manner in which they allow the building envelope to adapt to its environment:

- Material
- Form
- Composition

5.4.1 Material

There exists a wide range of phase-change materials that can be used in the building envelope; an example is switchable glazing, that changes its optical properties according to particular environmental parameters such as ambient brightness, solar radiation, indoor air temperature, and an electric charge.

However, some of the responses of phase-change materials are, according to the definition of an intelligent building envelope elaborated in Chapter 2, to be considered as a mere *reflex action, "a simple response which follows on directly and inevitably from the stimulus"* [Beukers & van Hinte 1998:45], upon which neither the envelope nor the occupant have the opportunity to exercise control.

Therefore, switchable glazing types such as photochromic and thermotropic glazing, as well as more static materials such as prismatic and laser-cut panels, are not discussed in this section. Even though they may usefully contribute to good indoor daylighting quality, they do not offer the envelope and occupant a choice in the manner in which they adapt themselves to changes in the environment.

The types of switchable glazing that are to be discussed in this section are (photo)electrochromic and gasochromic glazing, that are able to diversify their response according to the application of an electric charge or gas, respectively, which may be applied whenever desired, and sustained for any period of time.

In addition, two physical applications are discussed that may be classified as *artificial daylighting*, i.e., glazed panels in the walls or ceiling, the backside of which is illuminated by artificial light sources, that simulate daylight and its variations in intensity, directionality and colour. While this type of application strictly speaking is not related to the use of natural light sources, it might be conceived to be an opportunity to supplement and enhance daylighting strategies in particular circumstances, and is as such discussed in this section.

5.4.1.1 Electrochromic glazing

Electrochromic glazing changes its optical properties upon the admission of an electrical charge. This type of reaction makes electrochromic glazing an interesting material for an intelligent building envelope, where an adjustment of the visible light transmission of daylight apertures is a useful tool for the control of glare, view and privacy, and solar gains (Figure 5-28).

The electrochemical reaction is, in general, acquired by means of an electrical potential difference through the material. Thus, it is possible to control the material's change in optical properties either by means of controlling the potential difference in the material, or by controlling the electrical current flowing through the material. When the electric charge is removed, the electrochromic glazing may react in two manners, depending on its composition. On the one hand, the glazing may slowly return to its original - transparent - state; on the other hand, the electrochemical reaction may be sustained until a new electric charge is applied to bring the material back to its original state [Granqvist *et al.* 1997; Macrelli 1998].

[http://windows.lbl.gov/]

Figure 5-28: *Electrochromic glazing tested at the Lawrence Berkeley National Laboratory, in transparent (left) and coloured (right) state.*

Most architectural applications are based on the second type of electrochemical reaction, that needs to be removed by applying a new electric charge. This type of reaction is obtained by means of special coatings on the glass, which in turn affect the glazing's performance, lifetime and costs. By combining different kinds of coatings, the glazing's transmission and reflection characteristics, its spectral characteristics and its speed of coloration and bleaching can be influenced [Macrelli 1998; Moeck *et al.* 1998].

- **Transmission characteristics.** The range of visible light transmittance that can be obtained between coloured and transparent state, lies typically between 8 % and 88 %. This range, however, does often not sufficiently limit solar heat gains on sunny days; nor does it adequately reduce the excessive brightness of glare sources in the occupant's visual field, and additional shading devices need to be applied, particularly when VDT tasks are performed. The attenuation of excessive brightness in the occupant's visual field does permit the use of additional shading devices to be reduced, thus offering the occupant a non-distorted though coloured view. Moeck *et al.* [1998] further remark that the reduced transmittance of the electrochromic glazing in coloured state does not provide privacy to the occupant; additional shading devices are necessary when privacy from the outside world is required.

• **Spectral characteristics.** Most electrochromic glazing types feature very intense colours, such as dark blue obtained by the use of tungsten oxide; this colouration, of course, considerably influences the view of the occupant to the outdoor environment, as well as the colour appearance of daylight indoors. As this effect is often unfavourable, research efforts are being made to find more colour-neutral solutions,

Visible light transmittance T_v	Bleached $50 < T_v < 80$ Coloured $5 < T_v < 20$
Total Solar Energy Transmission TSET	Bleached 35 < TSET < 60 Coloured 10 < TSET < 20
Switching voltage	1-5 Volts
Switching speed	1 to 5 minutes
Memory	1 to 24 hours
Cyclic lifetime	10,000 to 1,000,000 cycles
Lifetime	5 to 20 years
Operating temperatures	-30^oC to 70^oC

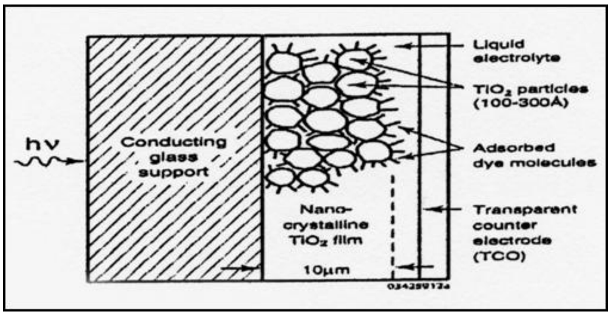
From [Macrelli 1998:309]

Figure 5-29: *Performance of electrochromic insulating windows.*

• **Response time.** According to Moeck et al. [1998], a response time of one to five minutes may be achieved for electrochromic glazing (Figure 5-29). In highly variable sky conditions, therefore, it is not advisable for the electrochromic glazing to follow all of daylight’s variations, and an intermediate transmittance level may be chosen instead, optionally supplemented with a different type of shading device.

5.4.1.2 Photoelectrochromic glazing

The flexilibility of electrochromic glazing may be increased by coupling it with a dye-sensitised solar cell electrode, where the voltage produced by the photovoltaic element can be used to start the electrochemical reaction of the glazing. This procedure is described by, amongst others, Deb [2005], Gregg [1997], and Macrelli [1998]. The principle of this unit is shown in Figure 5-30.



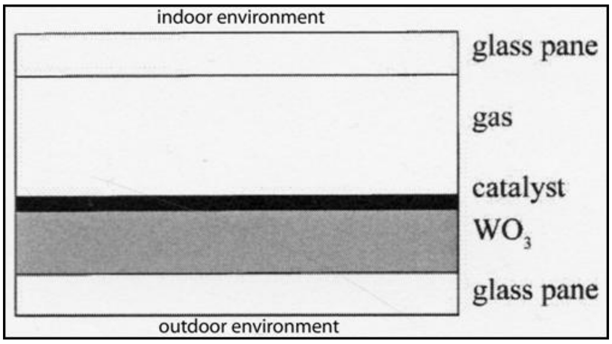
[Deb 2005:4]

Figure 5-30: *A dye-sensitised photoelectrochromic (PEC) solar cell device structure*

Photoelectrochromic glazing may function as a photochromic unit and as an electrochromic unit, as circumstances require. Thus, it becomes possible to choose the parameter the glazing is going to respond to; a change in visible light transmittance may be induced by ambient brightness as well as an electric charge, which increases the versatility of the glazing's adaptation to environmental conditions.

5.4.1.3 Gasochromic glazing

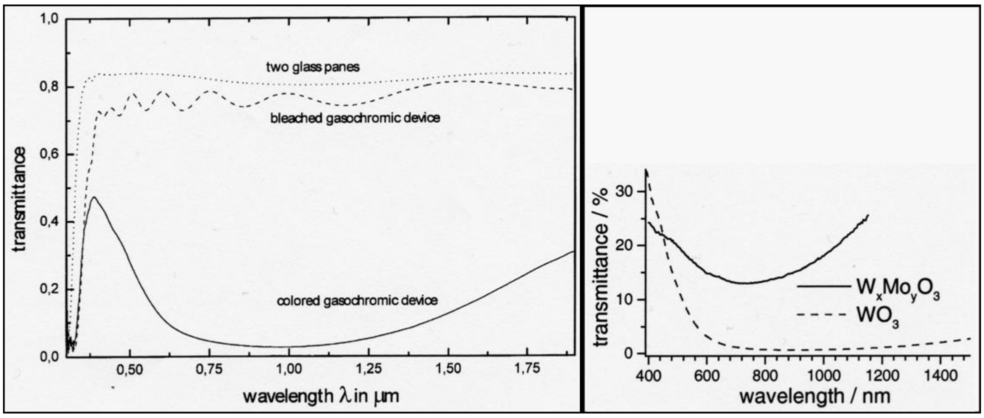
Another type of switchable glazing able to change its transmission properties as a response to an external command is *gasochromic glazing*. This type of glazing generally consists of a double-glazed window, with an active film (typically tungsten oxide (WO_3)) applied on the inside surface of the outer glass pane, followed by a thin catalyst layer (typically platinum (Pt) or palladium (Pd)), a layer of inert gas, and a layer of uncoated glass (Figure 5-31). The change in transmission characteristics is obtained by means of inserting strongly diluted gases: the insertion of strongly diluted hydrogen (H_2) causes a colouration of the WO3 film; the insertion of strongly diluted oxygen (O_2) reverses this process and brings the film back to a transparent, or bleached, state [Georg *et al.* 1998; Schweiger *et al.* 1998; Wittwer *et al.* 2004].



From [Schweiger *et al.* 1998:100]

Figure 5-31: *The structure of a gasochromic double glazing unit.*

- **Visual transmittance.** Wittwer *et al.* [2004] report a visible transmittance between 77 % in bleached state, and 6 % in coloured state (Figure 5-32), for a WO_3 film of 560 nm thickness. A thicker film could further reduce the visible transmittance in the coloured state, while the transmittance in the bleached state remains unchanged. Studies by Vitry *et al.* [2005] indicate a linear increase in colouration rate with film thickness for a thickness up to 500 nm; beyond 500 nm, the increase in colouration rate reduces considerably. The degree of colouration can be controlled by closing the valve and isolating the system as soon as the desired level of transmittance has been achieved. In coloured state, gasochromic windows allow for the distinction of images in the outdoor environment, though the view is strongly coloured [Schweiger *et al.* 1998; Vitry *et al.* 2005; Wittwer *et al.* 2004].



(left) [Schweiger *et al.* 1998:100]; (right) [Wittwer *et al.* 2004:310]

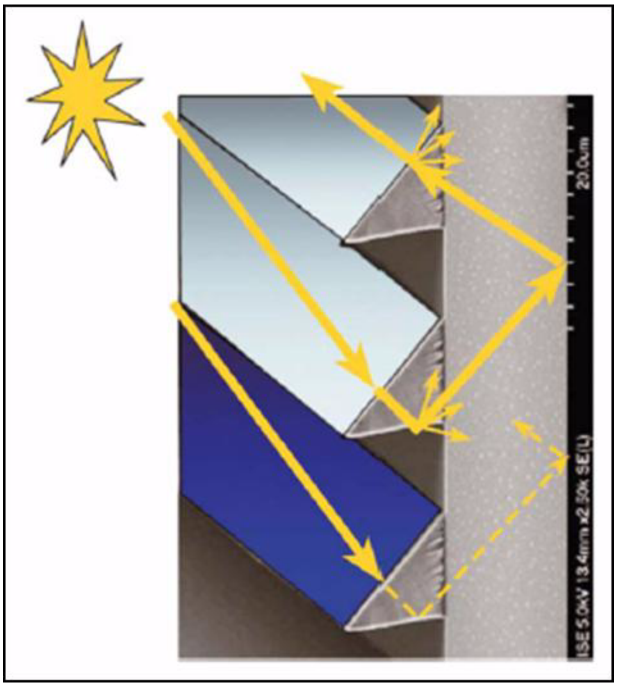
Figure 5 -32: *(left) the spectral transmittance of a gasochromic device in bleached and in coloured state; (right) the influence of the composition of the WO_3 film on the spectral transmittance of the gasochromic device.*

• **Spectral distribution.** The introduction of strongly diluted H_2 gases causes the glazing to appear blue in its coloured state. This colour appearance can, however, be mitigated by using a different mixture of oxides for the production of the active film; using $W_xMo_yO_3$ instead of WO_3, for example, produces a more neutral blue-grey colour appearance. This mixture, however, has a lower *colouration efficiency* or *ratio of change in optical density* [Georg *et al.* 1998; Wittwer *et al.* 2004].

• **Response time.** The colouring and bleaching rate of a gasochromic device can be increased by increasing a number of parameters, such as the H_2 concentration used to induce colouration, the porosity and thickness of the WO_3 film, and the pressure used to deposit the film. Furthermore, the Pt or Pd catalyst is indispensable to increase the response time of the WO_3 film [Georg *et al.* 2000a; Vitry *et al.* 2005]. Georg *et al.* [2000b] report on the performance of a prototype device that has been tested for two years and over 20,000 cycles. After two years, the transmittance (at 550 nm) of the glazing drops from 60 % to 24 % in one minute, and further to 10 % in ten minutes. The bleaching process is reported to occur more quickly; 50 % transmittance is reached after one minute, and after three minutes the original state has been restored.

• **Comparison to electrochromic glazing.** Gasochromic and electrochromic glazing both use tungsten dioxide films to obtain colouration of the glazing unit, and thus suffer comparable problems with respect to the colour appearance of the glazing in the coloured state. Also the lowest achievable visual transmittance is similar, and, as mentioned in the previous section, insufficient as glare protection. Also the energy needed to activate a gasochromic window is similar to that of an electrochromic window. With regard to the manufacturing process, gasochromic glazing has a simple coating structure, and the use of WO_3 sputtered films allows for manufacturing on a large industrial scale. Contrary to electrochromic glazing, there is no need to include conducting electrodes in gasochromic glazing; however, a gas distribution system does need to be installed [Georg *et al.* 1998; Vitry *et al.* 2005; Wittwer et al 2004].

• **Combination with other daylighting devices.** While electrochromic devices are being attempted linked to the use of photovoltaics, gasochromic coatings can be combined with passive daylighting elements such as prismatic materials; a conceptual application is shown in Figure 5-33.



[Wittwer *et al.* 2004:311]

Figure 5-33: *Gasochromic coatings can be combined with passive daylighting elements such as prismatic devices.*

- **Stability.** Prototypes of gasochromic glazing units are being tested in full-scale at the Fraunhofer ISE in Freiburg, Germany, as part of a larger European test of switchable glazing (SWIFT). The units have been tested with 20,000 switching cycles over a period of 2 years at 20^{o}C without any apparent damage. However, research efforts are being made with regard to the stability of the gasochromic coatings, as they exhibit degradation characteristics with regard to response time, and delamination over time [Wittwer *et al.* 2004].

5.4.1.4 Lightwall "Emotion" (Zumtobel Staff / Luxmate)

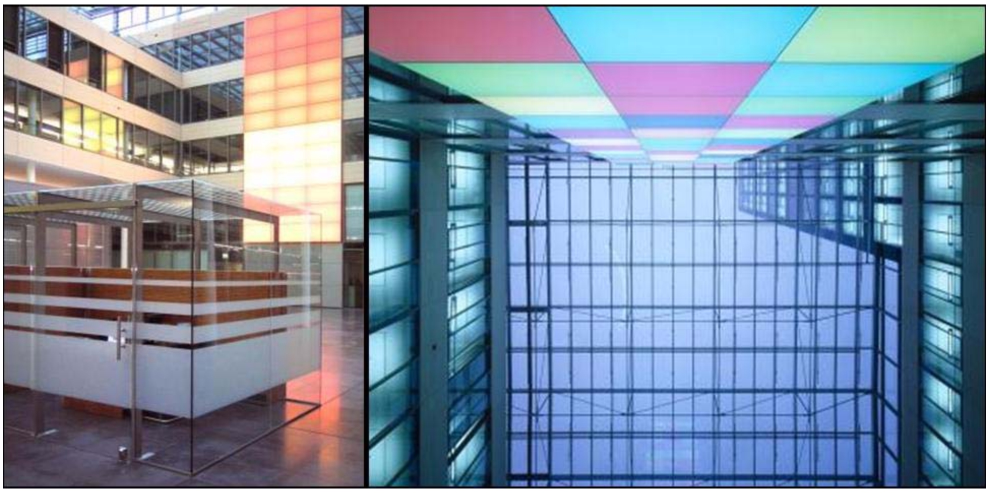
The first example of artificial daylighting is a lightwall with a variable colour appearance, located in the atrium of the *Stadtwerke Bochum GmbH* in Bochum, Germany (Figure 5-31). This building, designed by *Gatermann + Schossig Architekten* and completed in 2004, is further discussed in Section 5.4.3.1 for its particular facade design. The user interface that accompanies the lighting control system was already described in Section 5.2.2.3.

(left) [http://www.germanarchitects.com]; (right) [http://www.gatermann-schossig.de] © Barbara Staubach

Figure 5-34: *The Stadtwerke Bochum GmbH, designed by Gatermann + Schossig Architekten; the atrium features a lightwall with variable colour appearance.*

The lightwall, developed in co-operation with Zumtobel Staff, consists of 36 rectangular cubes (Figure 5-34). The construction is about 50 cm deep, featuring a frame with semi-transparent foil lit from behind by 448 fluorescent lamps. A combination of various lamp colours and filters is able to produce all colours desired, and each of the cubes may be controlled individually. The directionality of the lighting is changed by installing lighting with various distribution characteristics. Different light settings are possible, for example according to time of day or season, or a specific function.

The lighting control of the cubes, based on Zumtobel's *Active Light* concept, is developed to reproduce characteristics of daylight's variations in intensity, colour and directionality and thus manipulate the occupant's perception of colour in the indoor environment, as circumstances require (Figure 5-35). The colour appearance of the cubes can be made to change slowly so as not to be perceived by the occupants.



[http://www.gatermann-schossig.de] © (left) Gatermann + Schossig; © (right) Rainer Rehfeld

Figure 5-35: *The colour appearance of the lightwall can be made to vary according to the time of day, the type of weather, and the performance of specific functions*

This concept may also be installed in other types of spaces such as offices and commercial buildings, and any other application where dynamic lighting is desirable. Luminaires of various sorts, wall and other room surfaces can be involved in supplementing the distribution and appearance of natural light and optimise the indoor luminous environment for the building occupant.

While it generally is advisable to maintain daylight's colour rendering characteristics to the hightest extent possible, for particular functions, weather conditions, or times of day or season, it may be appropriate to supplement daylight's colour appearance with this type of artificial lightwall. On a dull day, for example, the cubes can be used to create a more cheerful mood indoors, on request of the building occupant.

A further example is the use of neutrally coloured lightcubes in a work environment shared by several people to reduce brightness contrasts across the room and augment the adaptation luminance at increasing distance from the daylight apertures, when the building envelope itself it not able to provide suitable conditions. Additionally, a lightwall may be used to create an appropriate balance of direct and indirect illumination in the indoor environment when frequent interreflections cause daylight to lack a strong angular component.

This information was extracted from the following sources:

- IntelligenteArchitektur **50**:34-43
- http://www.gatermann-schossig.de
- Communication with Marc Gatzweiler, Gatermann+Schossig Architekten
- http://www.zumtobelstaff.com/activelight
- Brochures provided by Zumtobel Staff
- AIT (Architektur-Innenarchitektur-Technischer Ausbau) April 2005 pp. 160-162
- http://www.germanarchitects.com

5.4.1.5 Lightwall "SIVRA" (iGuzzini)

While in the previous example the principle of the lightwall and artificial daylighting only was applied in the atrium, the *SIVRA* system developed by *iGuzzini* is specifically designed for applications inside workspaces. The lighting system SIVRA (Sistema di Illuminazione Variabile a Regolazione Automatica) is a daylight-simulating skylight originally designed for highly automated work environments without access to daylight. The system aims to increase ambient stimulation by means of light that, similar to daylight, constantly varies in colour and intensity (Figure 5-36). The variations are achieved by means of fluorescent lighting of various colour temperatures, combined with halogen lamps. At particular times, illuminance levels of 2,500 lux are provided, in order to create arousal and increase task performance [Scuri 2000].

[Scuri 2000:15]

Figure 5-36: *The SIVRA artificial skylights, installed in a control room, varying in colour and intensity during the course of time.*

The skylights have been tested by Boyce *et al.* [1997] during night-shifts in control rooms without access to daylight. Different lighting scenarios were investigated for their influence on the workers' circadian rhythm, emotional state and task performance. According to the authors, the daylight-simulating skylight is indeed able to improve the task performance of workers on the so-called *graveyard shift* (midnight to 8 AM), with an increase in wakefulness due to exposure to bright light. For relatively simple tasks, however, no statistically significant effects were found.

It is further suggested by Scuri [2000] that this type of *biologically significant* light also may be applied in a normal work environment during daytime, making workers more active, more sensitive to exernal stimuli, and more attentive. There are, however, particular parameters to be taken into account when using this type of system to supplement daylighting strategies in office spaces:

- **Access to daylight.** A first requirement would be to use these artificial skylights, or other types of daylight apertures (Figure 5-37), as supplement to daylight and not as replacement, first of all, due to the *Biophilia hypothesis,* discussed in Chapter 3, that describes the human need for contact with and a view to the outdoor environment. In addition, there are indications that people react differently to artificial than to natural light sources, with regard to glare tolerance, visual fatigue, and the pleasantness of the light.

[Scuri 2000:12]

Figure 5-37: *The effect of artificial daylight apertures on the colour appearance and atmosphere of the room*

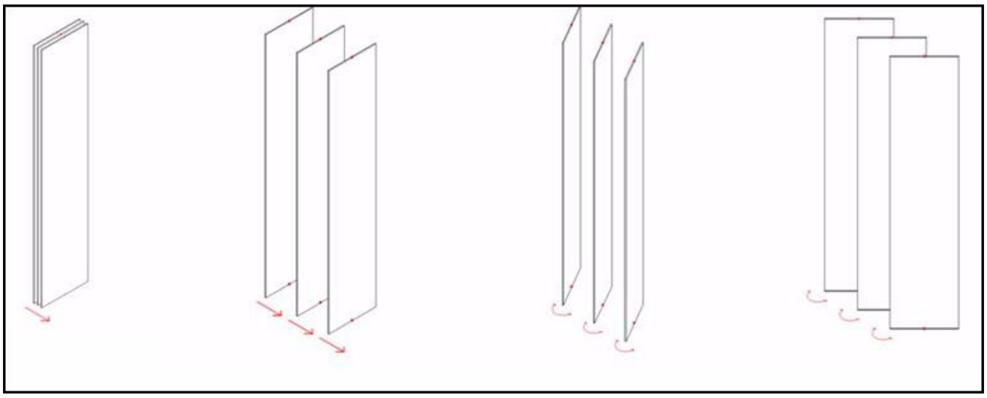
- **Individual control.** In office spaces, this type of artificial daylight might be used as a remedy for the typical early afternoon loss of concentration, with a variation in light intensity, directionality and colour adjusted to user requirements. As discussed in Chapter 3, however, such stimulants are likely to be considered as stressors by the building occupants, unless introduced at their particular request.

• **Arousal.** While it is indicated that high illuminance levels may create arousal and increase task performance, there is no indication that this effect can be sustained over time; neither do scientific circles agree on the light level needed to obtain arousal. In addition, according to several researchers, arousal brought forth by artificial light sources is not necessarily positive; on the contrary, it is suggested that people probably should not be exposed to fluorescent light of high illuminance for a prolonged period of time [e.g., Küller & Wetterberg 1993].

• **Energy efficiency.** The extensive use of high intensity light can be expected to strongly increase lighting energy costs as well as the building's cooling load. A potential counterargument would be that, over the life cycle of the building, energy costs are compensated for by the increased productivity of the employees. This argument, however, is only valid when the comfort and productivity of the workers in fact increase due to the use of this particular lighting system, not only during night shifts in control rooms, but also in offices and classrooms. In addition, it may seem wasteful to use high-intensity artificial lighting during daytime.

5.4.2 Form

Physical applications may also influence indoor daylighting quality by means of an adaptation of their physical form. This type of adaptation mainly covers *louvres, shutters and blinds*, elements that are rotated and/or relocated within the building envelope, around the elements' horizontal or vertical axis (Figure 5-38). As this type of adaptation is easy to spot, it often plays a prominent role in the visual expression of the building envelope towards the outside world. The elements may be composed of a variety of materials and colours, and feature different types and degrees of flexibility.



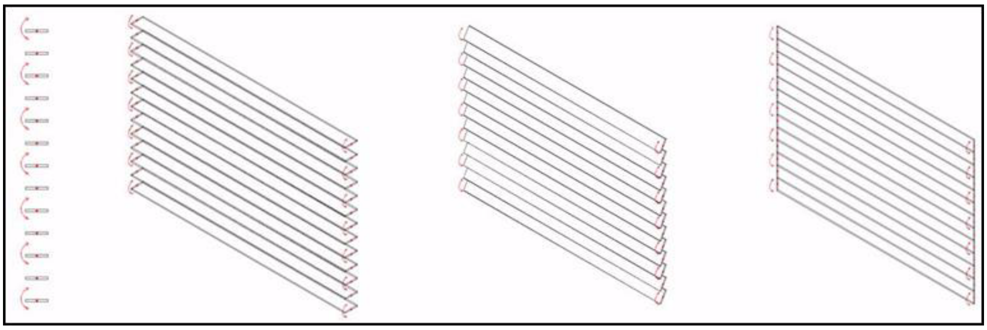
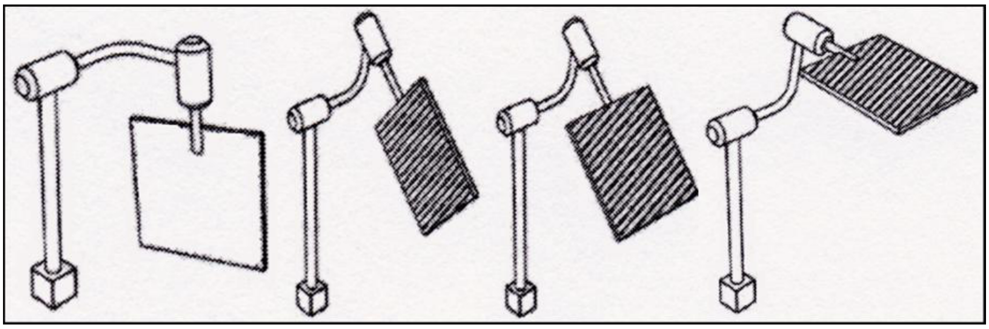


Figure 5-38: *Rotation and relocation - a selection of adaptation characteristics for louvres, shutters and blinds.*

In addition, *heliostats* are discussed, the components of which rotate around their axis in order to track the path of the sun (Figure 5-39), often with the help of soft computing algorithms.

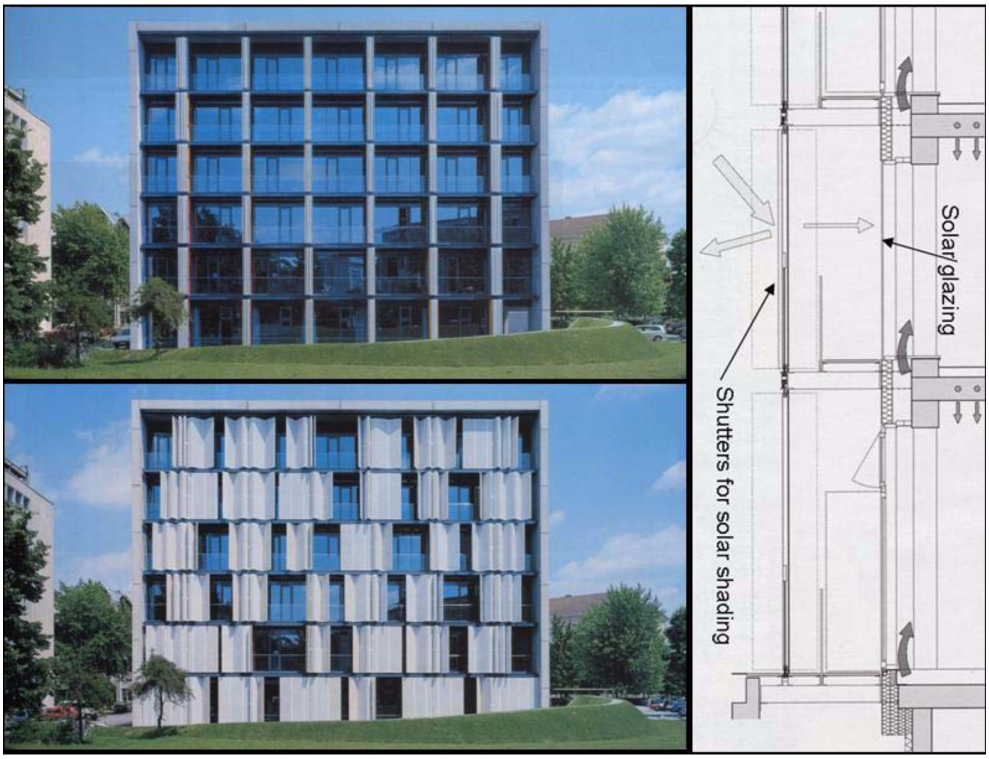


From [Alata *et al.* 2005:1244]

Figure 5-39: *A selection of adaptation characteristics for sun trackers.*

5.4.2.1 Solar shutters (Biokatalyse, TU Graz)

A first example of the adaptation of the physical form of the building envelope can be found in the Biokatalyse laboratory building at the TU Graz in Austria, designed by Ernst Giselbrecht and completed in 2004. The south facade of this building consists of a double skin with storey-high solar glazing for the inner layer, an outer skin consisting of solar shutters, and a cavity of one meter width (Figure 5-40). The shutters are moveable across a horizontal axis parallel to the facade, and tiltable around their own vertical axis. Consisting of perforated aluminium, the shutters are semitransparent, with one coloured and one neutral surface.



(left) [IntelligenteArchitektur **48/49**:51] © Paul Ott; (right) From [IntelligenteArchitektur **48/49**:55]

Figure 5-40: *Moveable and tiltable shutters at the laboratory building Biokatalyse at TU Graz; the shutters are located in the outer layer of a double skin facade, as shown in the section on the right.*

The shutters, placed on the exterior of the facade, are controlled manually by the building occupants. They are mainly applied to reduce solar heat gain indoors when desired. In addition, the shutters can be used to alter the visible light transmittance of parts of the building envelope.

In the context of an intelligent building envelope, this type of shutters would equip the envelope with partial control over the admission of daylight to the indoor environment. By adjusting the position of the shutters, and tilting them around their vertical axis, the transmission characteristics of the envelope can be made to vary according to the incidence angle of the incoming daylight, determining which limited portion of sky and site is allowed to influence indoor daylight levels. Moving and rotating the shutters allows for indoor daylight distribution to be altered, for instance by having more light pass through the envelope onto specific room surfaces. In this manner, walls may be brightened and distribute light further into the room by means of interreflections (Figure 5-41).

[IntelligenteArchitektur **48/49**:54, 57, 52] © Paul Ott, Graz

Figure 5-41: *The solar shutters allow for a differentiated treatment of daylight and visual contact across the facade.*

The perforated shutters also influence the occupants' experience of glare and veiling reflections. In order to avoid direct glare, the shutters may be positioned in the occupant's line of sight of the glare source; by rotating them, the required degree of opaqueness is provided to either reduce the apparent brightness of the glare source, or completely block it from the occupant's visual field. As the shutters can be moved horizontally to cover only part of the daylight aperture, they allow, to a certain degree, for a localised treatment of glare risk, leaving the rest of the daylight aperture unobstructed. This type of treatment could be exploited further by having the shutters move and rotate independent of each other for a localised treatment of glare risk, instead of having them attached as in the Biokatalyse building (Figure 5-42).

In this manner, glare treatment can be adjusted to the position and view angle of the occupant, while the rest of the aperture provides ample light and view. This type of glare prevention would also require a limited amount of envelope adaptation with regard to the glare source.

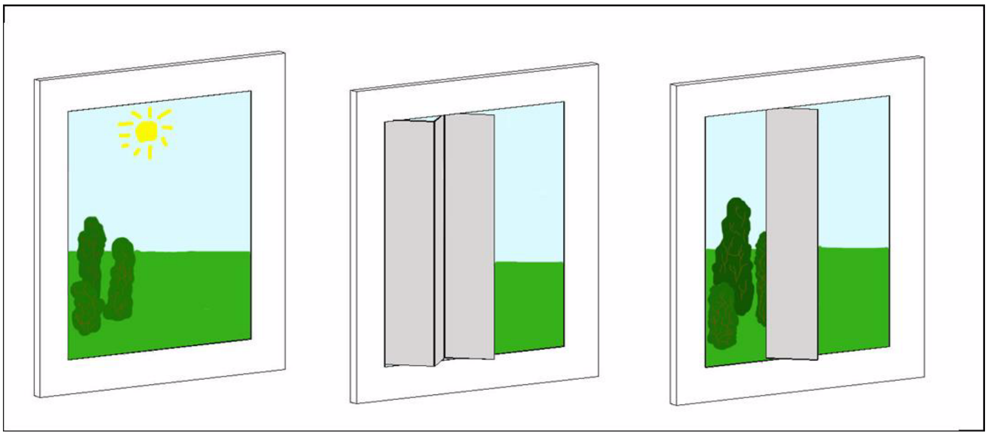


Figure 5-42: *Glare protection by means of shutters, as singular elements (right) or attached to each other (middle) influences the occupants' contact with outdoors.*

Localised use of the shutters would, in addition, provide the opportunity to choose which parts of the sky and site are visible to the building ocucpants. A limited use of shutters in the occupants' visual field may help to counteract the feeling of restricted contact with the outdoor environment that may arise in case of multiple envelope layers.

The relocation and rotation of coloured shutters may further be used to manipulate the occupant's perception of colour in the environment. Light reflected off or transmitted through the coloured shutters and into the indoor environment, will influence the colour appearance of daylight indoors, if desired. The use of shutters with one neutral side and one coloured one leaves the occupant a choice of the particular colour setting to be created, and provides the possibility to create variable atmospheres during the course of time. In case of direct sun, the perforated shutters may however give rise to disturbing shadow patterns. Care should also be taken to prevent the shutters from becoming a source of glare themselves, due to large brightness ratios between the perforations and the opaque parts of the shutters.

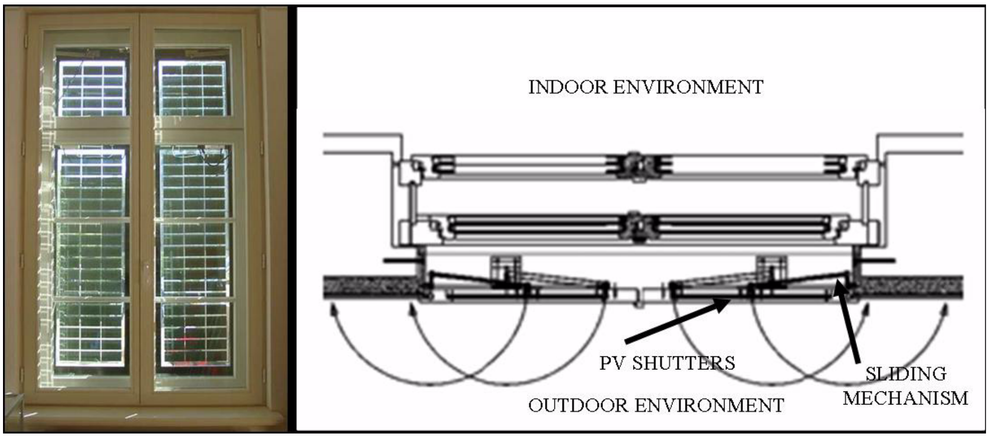
Further information regarding this project can be found in the following sources:

- IntelligenteArchitektur **48/49**:50-57
- http://www.giselbrecht.at

5.4.2.2 PV shutters (Colt International)

Solar shutters can be equipped with integrated photovoltaic cells, in order to combine solar shading with the production of electricity. German architect Astrid Schneider, for example, has developed and patented PV shutters in co-operation with Colt International, Sunways AG and Solarnova GmbH.

In these shutters, the PV modules are sandwiched between two panes of glazing. The shutters can be equipped with opaque or semi-transparent solar cells, and designed to match the specific building envelope. By variations in the transparency and colour of the PV cells, their arrangement and density in the shutter, and the transmission characteristics of the glazing, different degrees of transparency and solar shading may be achieved (Figure 5-43). Once the shutters are produced, however, these parameters are fixed and can not be altered.



(left) [http://www.solarintegration.de] © Astrid Schneider; (right) From [http://www.sunways.de]

Figure 5-43: *The semi-transparent PV shutters can be moved parallel to the building envelope; (right) a horizontal cross section of the PV shutters and the sliding mechanism.*

The shutters are equipped with a mechanism that does not rotate them but slides them to the side (Figure 5-43, right). In this manner, the PV cells are always parallel to the facade, and directed outwards. The advantage in daylighting is that, when no shading is needed, the shutters can be moved sideways for an unrestricted view, maximum daylight, while still producing energy. The sliding mechanism, operated manually or motorised, is constructed in such a manner as to always keep the solar-active part directed towards the outdoors. A small cavity between the shutters and the building envelope provides ventilation and increases the efficiency of the solar cells.

When the shutters are used to shade the indoor environment from direct sun, care should be taken to not lower indoor daylight levels to such an extent that artificial lighting is needed. To this purpose, the shutters may be used only in the lower section of the daylight aperture, while the upper area is left transparent for daylighting purposes. Alternatively, a varying degree of transparency may be applied along the height and width of the shutters, adjusted to the daylighting, view and solar shading functions of the envelope.

In addition, care should be taken to prevent the PV modules in the shutters from creating an uneven reflection of daylight in the occupant's visual field, due to brightness differences between the PV cells and the clear glazing, causing veiling reflections and glare. The PV cells may also create shadow patterns, as shown in Figure 5-44. While the use of semi-transparent PV cells will reduce the impact of such patterns, they may still cause glare and impede task visibility.

[http://www.sunways.de]

Figure 5-44: *The semi-transparent shutters create shading patterns, while allowing for a distorted view to the outdoor environment.*

Furthermore, the PV shutters, when in use, distort the view to the outdoor environment due to the patterns of the solar cells and their connections. The cells also influence the colour appearance of daylight indoors, which may no longer logically relate to local sky and site conditions.

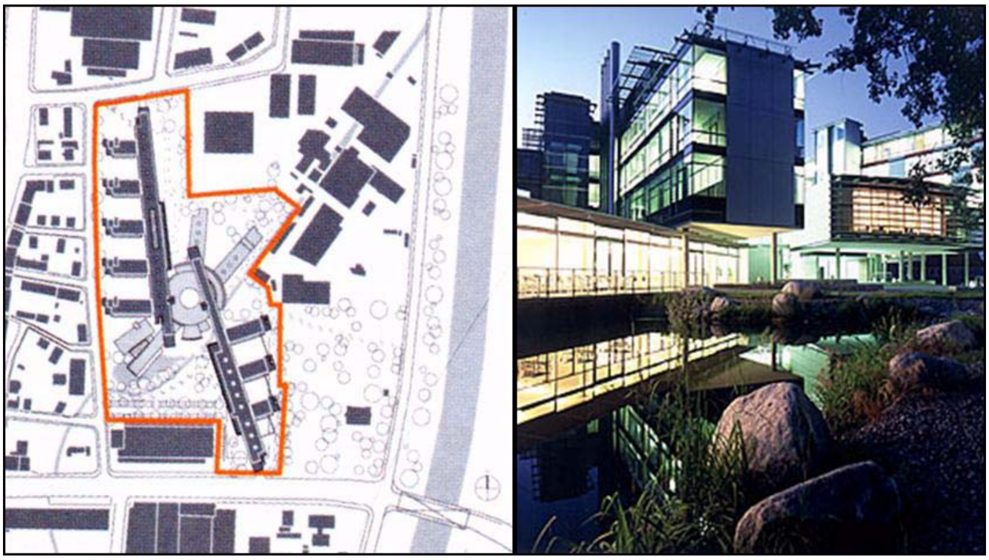
An interesting option would be to create PV shutters with a larger range of adaptation, for example by integrating photovoltaics into the solar shutters presented in the previous section. In that manner, it would be possible to move the shutters pararrel to the building envelope as well as rotate them around their own vertical axis, either to optimise solar access for the PV cells, or to provide the desired degree of transparency to the building occupant.

Further information may be obtained from the following sources:

- IntelligenteArchitektur **46**:(app)4
- http://www.sunways.de
- http://www.astrid-schneider.de
- http://www.solarintegration.de

5.4.2.3 Glazed louvres (LVA Schwaben, Augsburg)

An example of adaptation by means of rotation around a horizontal axis is provided by glazed louvres, as applied in the LVA Schwaben building complex in Augsburg, Germany; the project is designed by Hascher Jehle Architektur, and completed in 2002. Designed for an insurance company, the office building complex consists of interconnected, relatively small building blocks, surrounded by green and water surfaces (Figure 5-45).



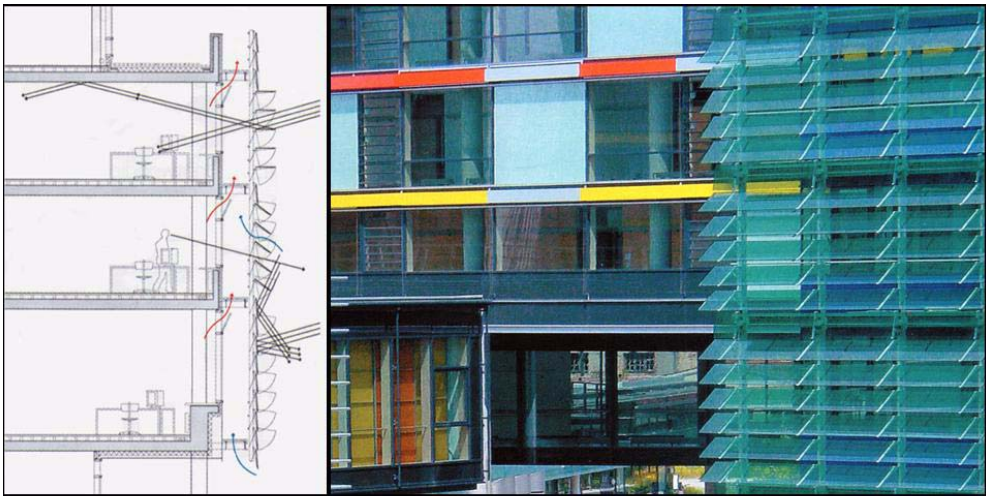
(left) [IntelligenteArchitektur **47**:44]; (right) [http://www.hascher-jehle.de] © Svenja Bockhop

Figure 5-45: *Plan and view of the LVA Schwaben building complex*

The design of the buildings aims for an optimal adjustment to local climate and site, providing ample access to daylight, and offering the building occupants a relief for the eyes from their focus on the computer screen all day long. The concept for the building envelope encompasses a diversity of daylighting elements such as fritted glazing, wooden louvres, and textile blinds.

One of the buildings, containing the archives, features a double skin facade with an outer skin consisting of glass louvres, designed in co-operation with Glastec GmbH. The louvres are made of solar glazing to lower solar heat gain. They can be tilted around a horizontal axis parallel to the facade, which enables them to block direct sunlight, or reflect it deep into the indoor environment.

The louvres can be tilted according to the desired effect and solar position (Figure 5-46), and are operated manually by the building occupants. Rotation of the louvres enables careful manipulation of the distribution of direct and indirect illumination indoors, and allows to obtain a variety of modelling effects. In closed, vertical position (parallel to the facade surface), the louvres allow for direct sun to be blocked and reflected outwards. In open, horizontal position (perpendicular to the facade surface), they reflect the incident sunlight inwards and upwards to the ceiling and upper wall area. Direct sunlight with a low, near horizontal incidence angle can be admitted indoors without being redirected.



(left) [IntelligenteArchitektur **47**:50]; (right) From [IntelligenteArchitektur **47**:46] © Werner Pawlok

Figure 5-46: *(left) vertical cross section of the building envelope,; the operation of the glazed louvres is differentiated per building floor; (right) view of the glazed louvres.*

In case of a bright outdoor environment, the louvres are not able to keep luminance levels and ratios in the occupant's visual field within acceptable limits. In addition, when the louvres are horizontal to reflect low solar angles deep into the room, direct sun may be admitted indoors in between the louvres, causing glare and creating strong shadows that might interfere with visibility, particularly in the task area. Each of the building occupants, therefore, has individual glare protection, which also can be used for privacy, shielding the occupant from the outdoor environment. In order to not obstruct the daylighting function of the glazed louvres, this internal glare protection needs to be placed so as to leave an opening above eye-height for light redirection.

Functional division would also be helpful for the glazed louvres in the external skin, for example by means of a differentiated tilt of the louvres across the height of the room, allowing a distinct treatment of glare risk and light redirection. In this manner, it would, for example be possible to prevent an upwards reflection of sunlight by louvres at the occupant's eye height. In this project, however, the louvres are controlled per storey, for a width of 20 metres across the facade. Thus, their position can not be adjusted to the individual building occupant.

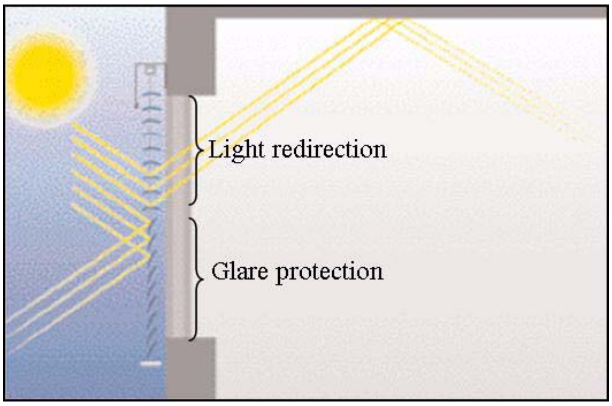
In addition, a functional division of the louvres' operation would allow for clear areas with an unrestricted view; as the louvres are not retractable, the double skin of the archive building creates an extra barrier between the in- and outdoor environment. Nevertheless, the restriction in this project is kept to a minimum as both skins are made of glass, provided the glazing is cleaned regularly. In addition, care has been taken to provide green and water surfaces around the building block to provide a view with a satisfactory composition and variability.

This information has been obtained from the following sources:

- IntelligenteArchitektur **47**:44-51
- http://www.hascher-jehle.de
- http://www.glastec-systeme.de
- Communication with Regine Jaeckel, Glastec GmbH

5.4.2.4 Venetian blinds (Warema / Genzyme Center, Cambridge MA)

Retractability and functional division can often be found in Venetian blinds, an element with a function similar to the louvres discussed in the previous section, though with a smaller scale and a different use of materials. In general, the element consists of horizontal slats that can be rotated around their own axis and retracted. The slats are often functionally divided into an upper and a lower part, for light redirection and glare protection, respectively (Figure 5-47).

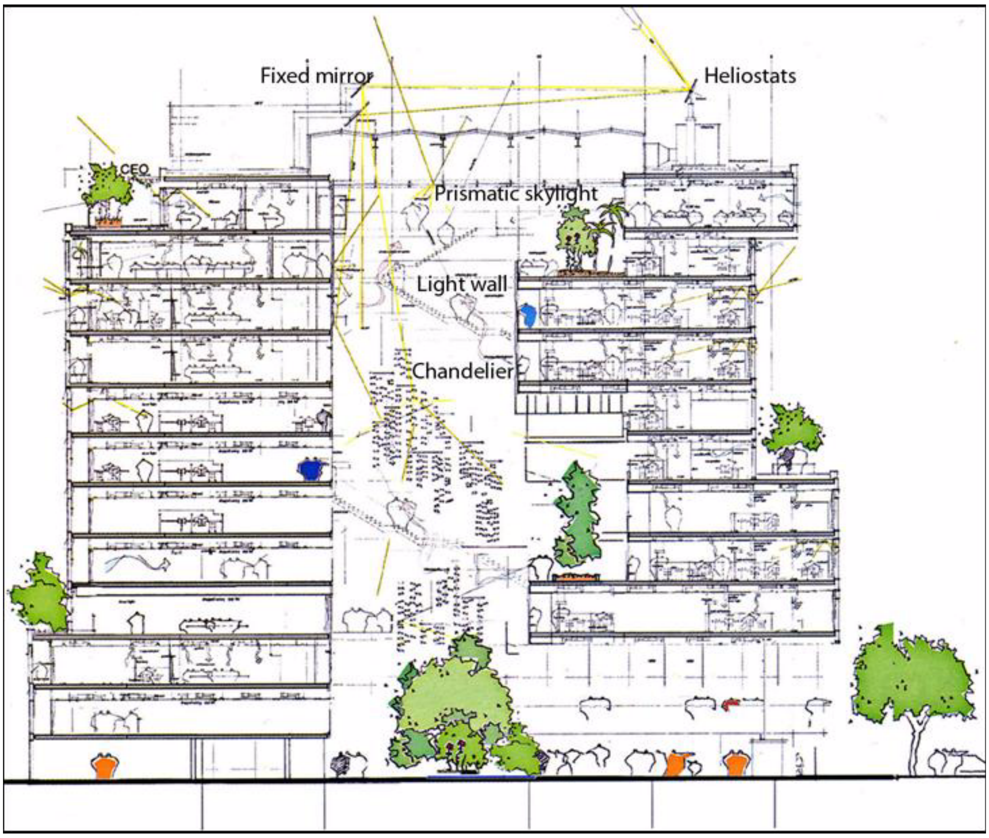


From [http://www.architectureweek.com]

Figure 5-47: *A functional division of slats into an upper and a lower part, for light redirection and glare protection, respectively.*

An example of the integration of Venetian blinds in the functionality of the building envelope can be found in the Genzyme New Head Office Center in Cambridge Massachusetts, USA, designed by Behnisch, Behnisch and Partners in co-operation with House and Robertson, and completed in 2003. The Genzyme building is located on an abondoned industrial site, and houses around 900 workplaces on a floor area of 27,900 sqm.

The plan of the building is designed in such a manner as to locate as many workplaces as possible in the perimeter of the building, where they have access to daylight (Figure 5-48). The building further features a 12-storey high atrium, prismatic skylights, and heliostats; the latter are discussed in Section 5.4.2.7. In addition, 40,000 sensors perceive environmental conditions in the in- and outdoor environment, as well as human activity. The lighting strategies were planned by Bartenbach Light Laboratory.

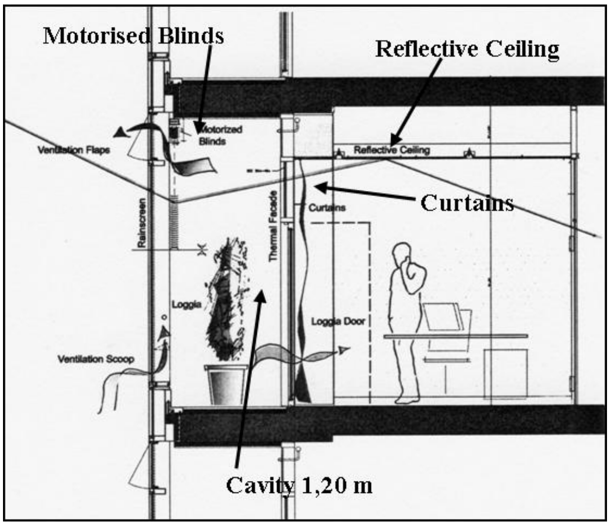


From [IntelligenteArchitektur **45**:26]

Figure 5-48: *A section of the Genzyme New Head Office Center, with atrium, heliostats and prismatic skylights*

The Venetian blind system used in this project, along with its control system, is provided by manufacturer Warema. The operation of the slats is automated with regard to solar position, illuminance data, temperature and neighbouring buildings, aiming to create an optimal balance between the redirection of daylight, the protection from glare, and the handling of solar heat gains. To take into account the influence of neighbouring buildings, the control system uses an annual shade diagram: the neighbouring buildings are registered on a plan of the environment, and their influence on the building envelope's access to direct sun is assessed for various reference points. Furthermore, the system is programmed according to scheduled activities in the building, with occupancy schedules adjusted to the individual rooms. The building occupants, however, are given the opportunity to override the control system.

The Venetian blinds are located in the cavity of a double skin facade, where they redirect incident sunlight onto the ceiling of the office for further distribution indoors. As the cavity is 1,20m wide, however, with a horizontal partition for each storey, the amount of light able to reach the office is severely reduced. In order to aid the redistribution of light indoors, the ceiling area near the daylight aperture is made of a specular-reflective material (Figure 5-49).



From [IntelligenteArchitektur **45**:33]

Figure 5-49: *The cavity of the double skin facade of the Genzyme building, with light-redirecting blinds and reflective ceiling.*

The blinds are designed to keep the luminance of the daylight aperture within acceptable limits, while maintaining contact with the outdoor environment to the largest extent possible. The slats have a specular-reflective upper surface with 93 % reflectance, which reflects direct sun incident on the slats outwards without converting it to thermal radiation. Half of the slat surface is perforated, in order to provide a (restricted) view outdoors even when the slats are closed in a near-vertical position. In this position, however, the perforations may cause high brightness ratios within the slats and a risk of glare. When the blinds are open, with the slats in a horizontal position, the perforated half of the slats reduces the chance of reflected glare when appearing in the occupant’s visual field, as opposed to an opaque slat surface of 93% reflectance. The highly-reflective slats and ceiling, however, may cause glare and veiling reflections, for workspaces in the perimeter as well as for those at a larger distance from the aperture.

[http://www.architectureweek.com] © Roland Halbe

Figure 5-50: *Two types of workplaces, with reflective ceiling, glass walls and low partition walls for increased daylight access.*

In order to provide access to daylight to the workplaces that are located at a larger distance from the daylight apertures, perimeter offices have glass walls towards the indoor environment, and workspaces are separated by means of low partition walls (Figure 5-50). For those people working at a distance from the daylight apertures, however, the only view is a view upwards towards the sky, which may be blocked by the light-redirecting slats. In addition, if the occupant with a workplace close to the aperture decides to close the blinds, view is blocked for the other occupants that do not have direct access to their own aperture, and this may cause frustration.

More information can be found in the following sources:

- IntelligenteArchitektur **45**:24-35, 62-63
- <http://www.behnisch.com>
- <http://www.warema-electronic.de>
- <http://www.earthsite.net>
- <http://www.architectureweek.com>

5.4.2.5 Stepped louvres “Genius” (Hüppelux)

While the slats discussed in the previous section need to be tilted considerably in order to provide glare protection, thus simultaneously obstructing view and access to daylight, stepped louvres are able to reflect direct sun out also in horizontal position. The *Genius* louvres by manufacturer Hüppelux, for example, developed in co-operation with the Fraunhofer Institute for Solar Energy Systems, provide this type of service (Figure 5-51). Another example of stepped louvres is found in the Stadtwerke Bochum, discussed in Section 5.4.3.1.

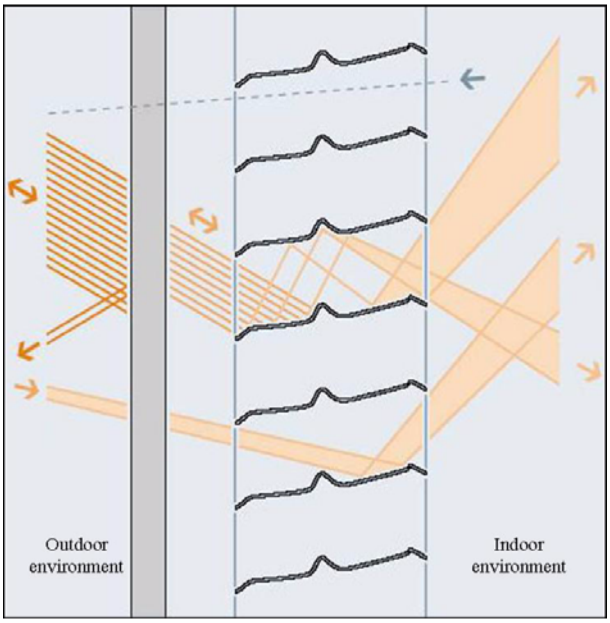
[http://www.hueppelux.de]

Figure 5-51: *The stepped profile of the Genius louvres*

The particular combination of shape and surface treatment of the slats provides glare protection in near-horizontal position for any solar incidence angle higher than 40 degrees. This limits the obstruction of a view to the outdoor environment, and, in addition, reduces the need for adaptation to varying solar visibility. The system may be retracted when not in use.

The upper slat surface has a matte white lacquer finish, with a reflectance of more than 90 %; the lower slat surface, on the other hand, has a light grey lacquer finish. Direct sunlight is partially reflected outwards in order to limit solar heat gains. The rest of the light is redirected into the indoor environment in three different manners, depending on the area of incidence on the slats (Figure 5-52).

The width of the slat section measures 5 to 8 cm, and is functionally divided into two areas. Light incident on the outer half of the slats is diffused by means of several interreflections in between the slats, after which most of the light is redirected to the ceiling and upper wall area. Some of the light, however, is redirected downwards from the grey, lower slat surface. Light incident on the inner half of the slats is reflected upwards in the room, without interreflections in between the slats.



From [http://www.hueppelux.de]

Figure 5-52: *The stepped louvres are designed to reduce the risk of glare and solar heat gain, while simultaneously redirecting daylight and providing a view to the outdoors.*

The lower slat surfaces are lacquered grey in order to reduce the glare effect of the louvres when they reflect incoming daylight. In addition, the neutral colour finish of the slats does minimise their influence on the colour appearance of the indoor environment. Combined with frequent interreflections between the slats, however, the grey surface finish also reduces the light output of the system considerably due to its lower reflectance. In addition, the light grey surfaces absorb part of the light and thus add to solar heat gains [Köster 2001].

For solar incidence angles lower than 40 degrees, direct sun is able to enter the indoor environment without being diffused; in case of glare risk, however, the slats need to be tilted to block the sun. Glare caused by bright sky conditions or reflections off neighbouring buildings can not be averted by the near-horizontal slats either. The louvre system as a whole may, due to the frequent interreflections, also appear as extremely bright compared to the surrounding room surfaces. This effect is counteracted by the redirection of light both upwards and downwards, which brightens the surfaces around the aperture and softens the contrast ratios in the room.

Due to the particular shape of the slats, the indoor environment can be darkened completely when the slats are closed in near-vertical position, for example in case of presentations, or to ensure absolute privacy.

In the context of an intelligent building envelope, it may be interesting to design this type of system with an adaptable distance between the slats. If there is no glare risk, the distance between the slats may be quite large so as to allow, on the one hand, more daylight to penetrate the room, and, on the other hand, a more unrestricted view to the outdoors. In case of bright sky conditions, low sun and reflections off neighbouring buildings, rather than tilting the slats, the distance between the slats can be reduced to increase the light reflected outwards, and the rest of the light interreflected more frequently before being released in the indoor environment.

The information regarding *Genius* louvres was obtained from the following sources:

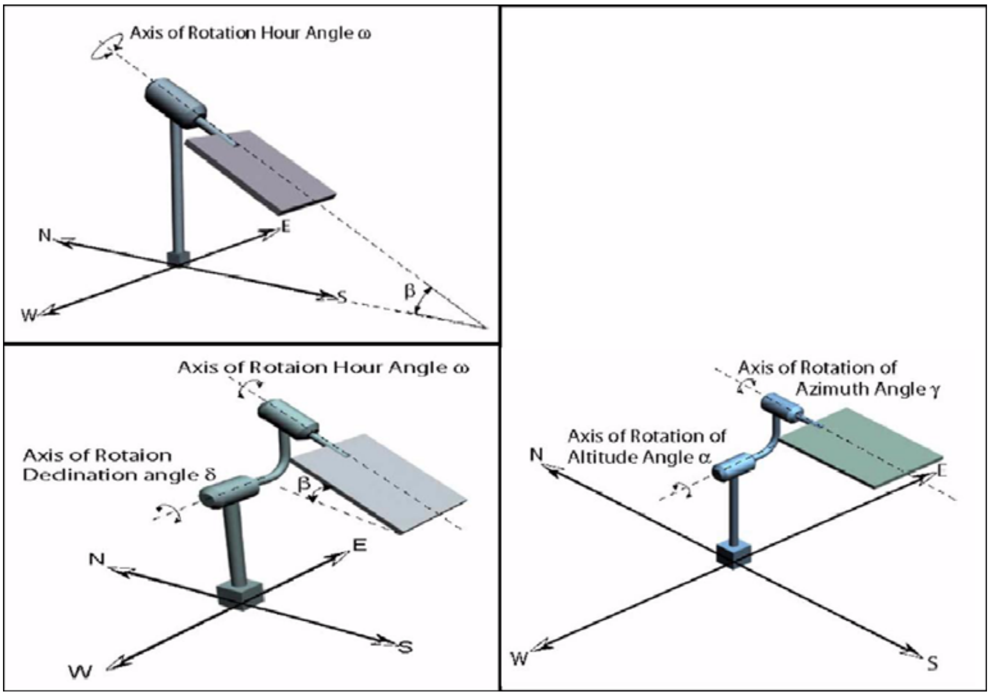
- IntelligenteArchitektur **46**:63
- http://www.hueppelux.de
- Communication with Christoph Farrenkopf, Hüppelux

5.4.2.6 Sun tracking systems

Daylighting not only involves the admission and distribution of daylight indoors, but also the collection of light from different sources outdoors to the appropriate daylight apertures. An example is the use of a sun tracking system that follows the path of the sun and correspondingly, in combination with additional optics such as prismatic systems and lightpipes, collects the available light indoors.

There exists a wide range in sun tracking systems, sorted according to the parameters chosen for the tracking control, such as [Alata *et al.* 2005]:

- **Temporal variations:**
  - Continuous tracking
  - Step tracking, typically 4 minutes or one degree movement by the sun
- **Perception system:**
  - Controlled by a timer, which is sensitive to external disturbances
  - Controlled by photosensors, that are energy consuming
  - Combining timer with sensors to compensate for their respective weaknesses
- **Spatial variations:** mobility of the tracking component, typically (Figure 5-53):
  - Rotation around one axis, according to site latitude
  - Rotation around 2 axes, according to site latitude and solar declination angle
  - Rotation around 2 axes, according to sun azimuth and elevation angle



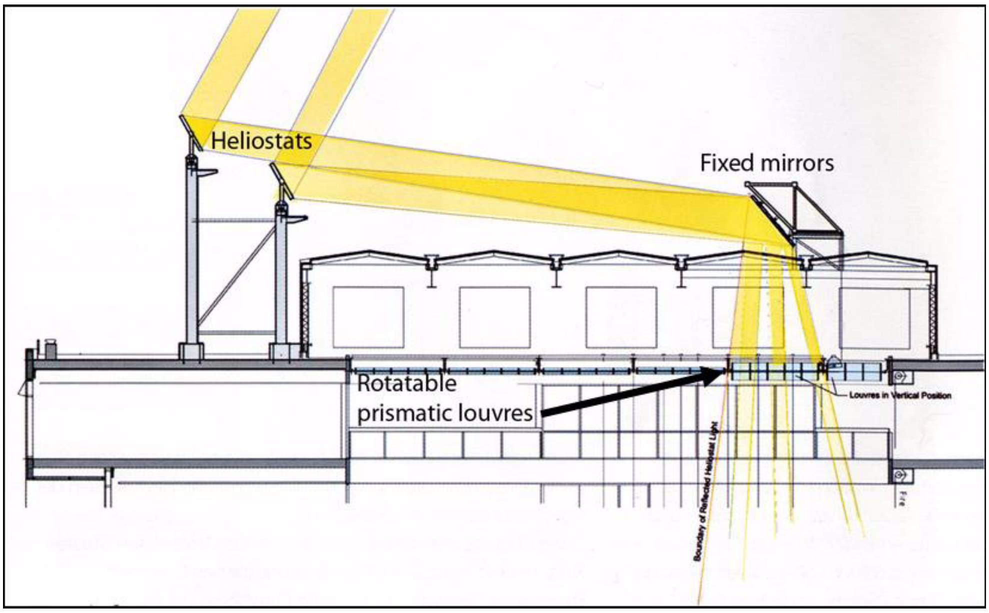
[Alata *et al.* 2005:1233-1235]

Figure 5-53: *Sun tracking systems with a different degree of mobility; (upper left) one axis tracking according to site latitude; (lower left) two axis tracking according to latitude and solar declination angle; (lower right) two axis tracking according to sun azimuth and elevation angle.*

In order to control this mobility, soft computing algorithms may be used. Alata *et al.* [2005], for example, describe a heliostat control system based on fuzzy systems and artificial neural networks.

5.4.2.7 Heliostat (Genzyme New Head Office Cente, Cambridge MA)

The Genzyme New Head Office Center, that was discussed for its lightwalls in Section 5.4.1.3, features a 12-storey atrium in the core of the building that is intended to provide the surrounding work and meeting places with daylight. Sunlight is guided into the atrium by means of seven sun-tracking *heliostats* (located on the north side of the atrium) combined with fixed mirror systems (located on the south side of the atrium) (Figure 5-54).



From [Intelligente Architektur **45**:34]

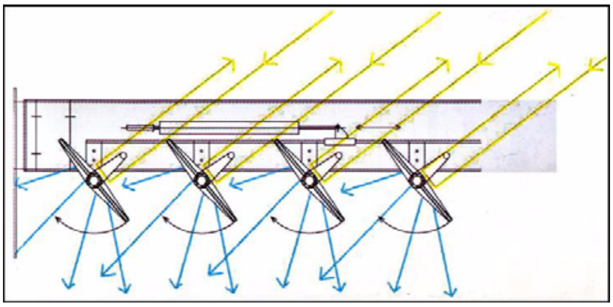
Figure 5-54: *Heliostats and fixed mirrors collect sunlight and guide it into the atrium.*

Upon entering the atrium, sunlight is filtered through a layer of adjustable *prisms* that provide solar shading, and distributed in the 12-storey depth of atrium by means of vertical, specular-reflective *lamellas*; the prisms and lamellas are tilted according to the time of day and season. Internal reflections inside the atrium are further increased by means of *daylight chandeliers*, with prism squares that reflect or transmit daylight according to incidence angle (Figures 5-48 and 5-55). The heliostats, fixed mirrors, and prism systems are manufactured by Bomin Solar GmbH.

[IntelligenteArchitektur **45**:35, 34] © Anton Grassl, Boston

Figure 5-55: *Some of the light installations in the atrium: light chandeliers and highly-reflective lamellas (left) and prism systems (right).*

The heliostats provide the atrium with sunlight in places and at times otherwise unaccessible, and create a cheerful atmosphere. As direct sun is used as a light source, however, in overcast sky conditions the equipment probably decreases the light levels in the atrium, making the environment appear gloomy. The system thus needs to be backed up by artificial lighting in order to provide a fairly stable luminous environment. In this project, metal halide lamps are used, the light of which is distributed by the same prisms as the natural light for continuity (Figure 5-56).



[IntelligenteArchitektur **45**:34]

Figure 5-56: *Prisms filter sunlight before admitting it into the atrium, according to the time of day and season. The system is backed up by artificial lighting.*

The lighting installations distribute daylight throughout the atrium, manipulating its intensity and directionality and providing interesting, though artificial, variations according to the time of day and season. There is, in addition, a risk of glare when the highly-reflective vertical lamellas and the prism chandeliers appear as extremely bright surfaces in the occupant's visual field.

More information regarding this project can be found in the following sources:

- IntelligenteArchitektur **45**:24-35, 62-63
- <http://www.behnisch.com>
- <http://www.bomin-solar.de>
- <http://www.earthsite.net>
- <http://www.architectureweek.com>

5.4.3 Composition

Also the composition of elements in the envelope may be used to enhance the envelope's adaptation. A first feature discussed in this section is the integrated design and use of artificial and daylighting strategies in the envelope. The integration of luminaires for artificial lighting into the building envelope provides a different kind of flexibility regarding the admission and distribution of (day)light into the indoor environment as well as the attunement of daylighting and artificial lighting strategies.

Already in [1966], Hopkinson *et al.* discuss the development of P.S.A.L.I. (Permanent Supplementary Artificial Lighting in Interiors), where, on the one hand, the operation of the artificial lighting system is controlled according to daylight availability, and, on the other hand, the window is designed to function optimally in co-operation with the location and output of the artificial lighting system. The authors criticise, however, the Swedish practise of installing artificial lighting near the window so as to provide a light distribution similar to that of daylight: it reduces the potential of light distribution in the depth of the room, aggravates the potential for glare and limits the flexibility of room geometry due to the need for a sufficiently high ceiling to reflect the light in the depth of the room (Figure 5-57). The examples discussed in Section 5.4.3 aim to solve these issues by integrating the artificial lighting system in the building envelope and having it co-operate with shading and daylighting systems.

[Hopkinson *et al.* 1966:431]

Figure 5-57: *The Swedish variation of P.S.A.L.I. (Permanent Supplementary Artificial Lighting in Interiors), with artificial lighting installed directly above the windows.*

A second type of composition discussed in this section is the use of ETFE foil cushions, a combination of membrane technology and pneumatic structures, that in a restricted range of application areas can be used to provide adjustable solar shading.

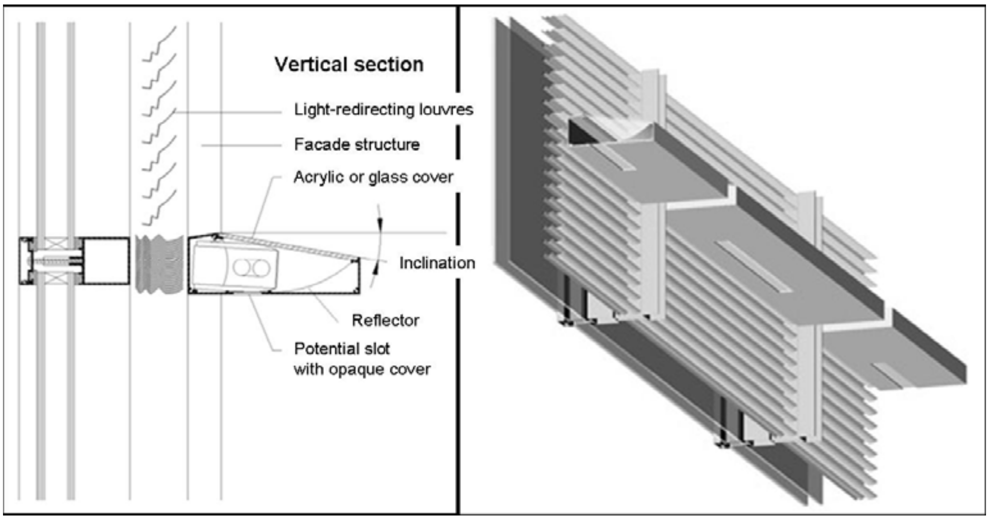
5.4.3.1 PRO-day (Stadtwerke Bochum GmbH, Bochum)

The Stadtwerke Bochum building complex consists of a 5-storey building with atrium and a 16-storey building tower (Figure 5-58). The project is designed by Gatermann + Schossig Architekten and completed in 2004. In co-operation with Köster Lichtplanung, a facade concept is developed that integrates artificial lighting with daylighting and solar shading (Figure 5-59).

[http://www.gatermann-schossig.de] © Barbara Staubach

Figure 5-58: *The building complex of Stadtwerke Bochum, with the PRO-day facade system developed in co-operation with Köster Lichtplanung.*

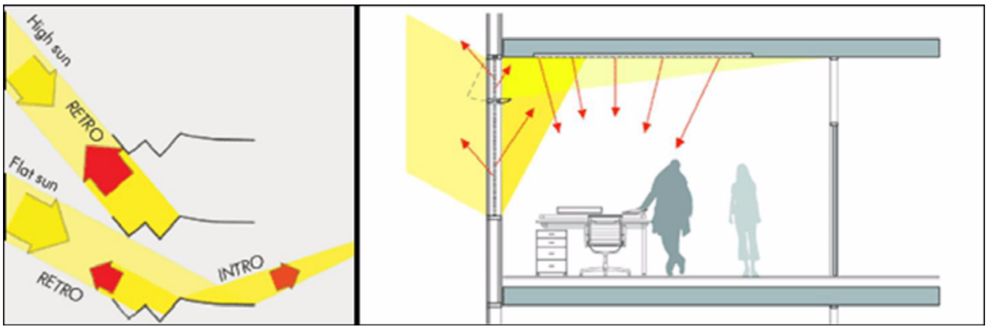
The design of the facade provides a range of adaptable solutions to achieve satisfactory luminance levels in the occupant’s visual field, and to illuminate different functional surfaces with an appropriate intensity.



From [http://www.koester-lichtplanung.de] © Köster

Figure 5-59: *The facade principle with integrated natural and artificial lighting.*

For daylighting and solar shading purposes, the facade uses stepped mirror louvres in combination with reflective ceiling elements. The stepped profile of the mirror louvres makes them angular-selective in their admission as well as distribution of daylight indoors. Depending on the incidence angle, light is reflected either outwards or upwards to the ceiling (Figure 5-60). According to Köster, 50 % of the solar energy admitted through the glazed facade is reflected out again by means of retro-reflection: sunlight incident on the two outer parts of the stepped louvres, is reflected backwards in the same direction, with a neglectable amount of absorption in the slats. With the stepped louvres sandwiched between insulating glazing panels, more than 90 % of the incident solar radiation would be reflected outwards [Volz 2004].



[http://www.koester-lichtplanung.de] © Köster

Figure 5-60: *The stepped louvres reflect incident sunlight outwards by means of retroreflection, or reflect it upwards to the ceiling.*

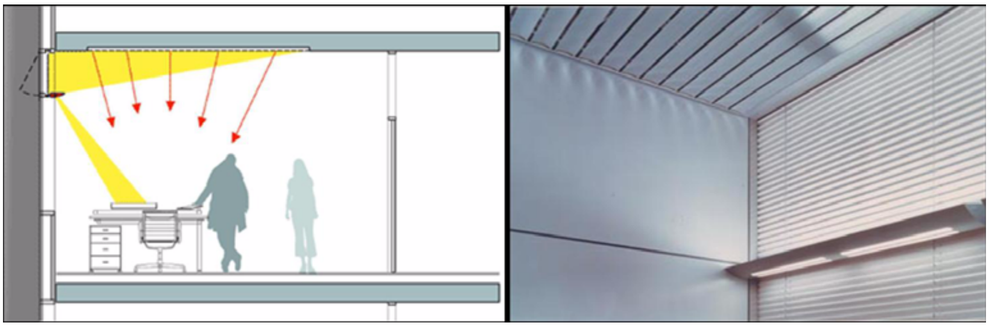
The tilt of the louvres with regard to solar incidence angle can be controlled separately for the upper and lower aperture area, in order to respond better to potentially conflicting demands of glare protection, daylighting and visual contact with outdoors (Figure 5-61). The louvres in the upper aperture area redirect light to the ceiling, and from there on to the work surface. The louvres in the lower aperture area can be set to light the task surface directly, or to reflect light up to the ceiling.

[IntelligenteArchitektur **50**:41] © Gatermann + Schossig

Figure 5-61: *The PRO-day facade balancing glare protection, daylighting and visual contact.*

In order to avoid glare while preserving a view to the outdoor environment, the stepped louvres in a horizontal position block direct sun with a high incidence angle (more than 45^{o}), and redirect light with lower incidence angle (25^{o} to 45^{o}) steeply upwards to the ceiling. This differentiation reduces the frequency of need for adjustment of the louvres' tilt. For near-horizontal solar angles, though, glare may still be an issue. In addition, by reflecting the light steeply upwards, the mirror louvres may cause reflected glare for specific view angles. When no glare protection is needed, the louvres can be retracted to provide an unrestricted view to the outdoor environment.

The integration of artificial lighting in the facade, enables the use of a mixture of indirect and direct illumination in a manner similar to daylighting (Figure 5-62). For indirect illumination, the luminaires send light upwards to the ceiling for redistribution in the room. In addition, direct lighting of the task surface is possible when desired. This concept of artificial lighting enables a more flexible layout of the work environment.



[http://www.koester-lichtplanung.de] © Köster

Figure 5-62: *The integration of artificial lighting strategies in the facade, providing a mixture of indirect and direct illumination in a manner similar to daylighting.*

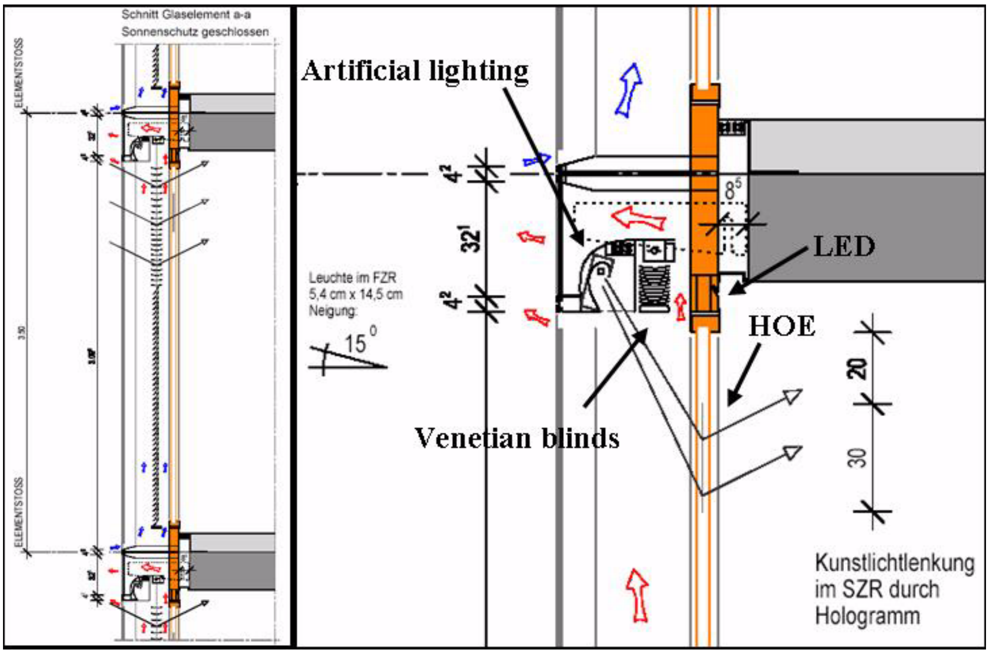
It is above all the adaptability and elaborate degree of co-operation between components, that makes up the potential of this facade design for use in the IBE concept: functional distinction within the facade, integration of daylighting and artificial lighting, and adjustable ceiling elements to redirect light and influence the brightness of distinct surfaces in the occupant's visual field, according to functional and individual requirements.

This information is obtained from the following sources:

- IntelligenteArchitektur **50**:34-43
- IntelligenteArchitektur **46**:64
- http://www.gatermann-schossig.de
- http://www.koester-lichtplanung.de
- Communication with Brigitte Köster, Köster Lichtplanung
- http://www.germanarchitects.com

5.4.3.2 TEmotion (Wicona / Hydro Building Systems)

TEmotion is a double-skin facade concept with integrated but decentralised facilities for natural and artificial lighting, heating, cooling and ventilation. The facade system consists of several types of modules that to a large extent are prefabricated; different types of modules are easily combined. Semi-transparent photovoltaic elements integrated in the facade modules harvest solar energy, which can be used to supply the different facade components with electricity, or sold to the electricity company in case of excess. The functioning of the facade can be controlled by the user or by automation, either decentralised or integrated in an overall building control system. In addition, the facade gives notice of any irregularities in its performance. The user interface of this system and its interaction with the lighting strategies was discussed in Section 5.2.2.4.



Provided by [Hydro Building Systems]

Figure 5-63: *Section of the TEmotion facade concept, with integrated daylighting and artificial lighting.*

Venetian blinds provide daylighting and shading, functionally divided onto the upper and lower slat area, respectively. The facade modules are in addition equipped to provide artificial lighting (Figure 5-63). The artificial lighting system is designed to provide a varying distribution, colour temperature, and directionality of light in the indoor environment when the availability, accessibility and/or controllability of daylight sources is insufficient to suit the occupants' needs and preferences. When the occupant requests more light, for example, the system evaluates whether this could be obtained by means of daylight, or whether artificial light needs to be used.

Two distinct types of artificial light sources are used in the facade: metal halide discharge lamps with a CCT of 3000K, and *light emitting diodes* (LED) emitting blue light. These light sources can be used to provide adequate illuminance and brightness levels in the occupant's visual field, with an appropriate incidence angle. In addition, the colour temperature of these light sources can, when requested by the occupant, be used to compensate for an unfortunate colour appearance of daylight indoors. On a dull day, for example, the various types of artificial lighting can create a more cheerful indoor luminous environment.

Provided by [Hydro Building Systems]

Figure 5-64: *The operation of the TEmotion facade concept using only daylight (left) or artificial light (right) sources.*

The integration of artificial lighting in the facade makes its influence on the indoor environment, particularly regarding the direction and distribution of light, more similar to that of daylighting (Figure 5-64). The incoming artificial light can in a manner similar to daylight be redirected or diffused, by means of *holographic optical elements* (HOE) on the inner facade layer. However, it also poses similar lighting challenges, such as how to lead light deep into the room, away from the light aperture. The opportunity to even out a typical uneven light distribution due to unilateral daylighting disappears without an additional artificial lighting system in the room.

Artificial lighting integrated in the facade also gives the opportunity to manipulate the occupant's perception of colour in the indoor environment, by altering the ratio between natural and artificial light in the occupant's visual field. As discussed in Chapter 4, the human eye easily adapts to gradual differences in colour temperature in a room, and it may be questionable whether a change in colour temperature induced by the envelope would be noticed, except when it creates a strong contrast to outdoor conditions.

Artificial lighting integrated in the facade may also be used to create an appropriate balance of direct and indirect illumination in the indoor environment. While it is possible to use artificial lighting to this effect regardless of its location - positioned in the indoor environment or integrated in the facade, the modelling effects and atmosphere created indoors will be completely different depending on the particular location of the artificial lighting. It may, for example, be difficult to provide directional light at increasing distance from the daylight aperture or envelope, where light predominantly arrives with reduced directionality due to frequent interreflections. The integration of artificial lighting systems in the facade also lowers the possibilities to provide light from various angles and thus reduce shadows and improve task visibility.

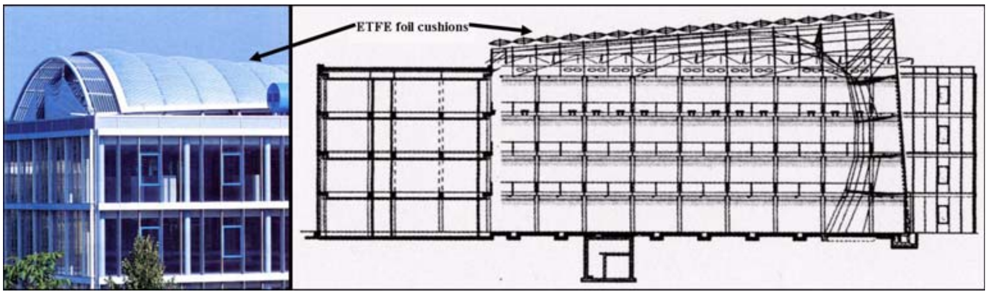
The information regarding this project was obtained from the following sources:

- IntelligenteArchitektur **50**:13
- http://www.hydro.com
- Communication with and documents provided by Dietmar Bruederl and Werner Jager, Hydro Building Systems

5.4.3.3 ETFE foil cushions (Festo TechnologyCenter, Esslingen-Berkheim)

An alternative to glazing systems can be found in the use of ETFE (*Ethylene Tetra Fluor Ethylene)* foil cushions, particularly applied in atrium and other glazed roofs. Membrane technology has long been available as an alternative to glazing, but with limited success due to poor stability and durability. The development of ETFE during the past few years, however, has improved the potential for application of membrane technology in building design. ETFE, a co-polymer of ethylene and Teflon® is stable and able to resist chemical and UV influences; its optical properties are not reduced over time [Robinson-Gayle *et al.* 2001].

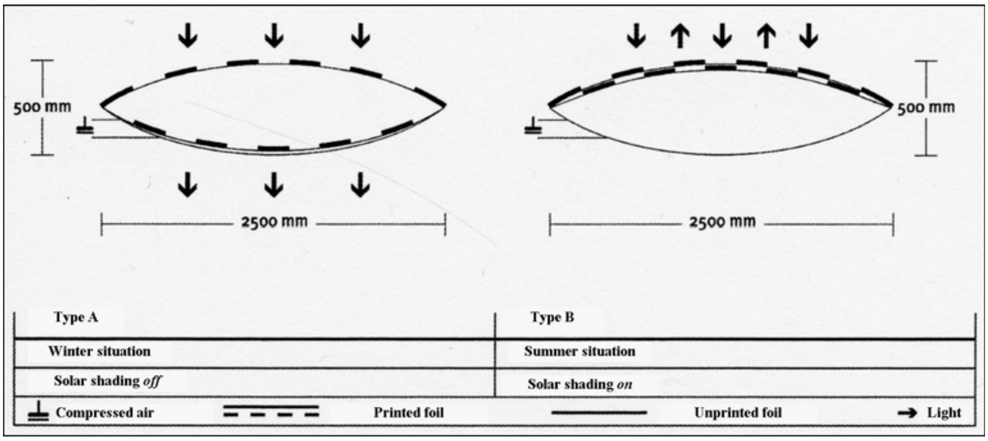
ETFE foil cushions consist of multiple layers of ETFE foil (each typically 100-200 μm thick), that have been heat sealed and then clamped in an aluminium or steel frame. The cushions can measure up to 25 m by 3.5 m. Due to the multiple layers, the cushions can be inflated to form a roof with a flexible curvature; to this purpose, the cushions are pneumatically inflated by means of a small pump to a pressure of 250-400 Pa. Due to internal pressure, the cushions are prestressed, which enables them to accommodate external loads due to, for example, snow. The air pressure in the cushions is monitored continuously, and topped up by an electric fan if necessary. Compared to glazed atrium roofs, the foil cushions form a light-weight construction. As ETFE is anti-adhesive, the need for cleaning is lowered considerably. The cushions, however, are acoustically transparent, which may form a serious obstacle for successfull application [Robinson-Gayle *et al.* 2001; Tanno 1997].



(left) [IntelligenteArchitektur **31**:30] © A. Braun, Hameln; (right) From [IntelligenteArchitektur **31**:32]

Figure 5-65: *ETFE foil cushions applied in the Festo TechnologyCenter; (left) an external view of the atrium roof; (right) a cross section through the atrium.*

The concept has been applied, amongst others, in the Festo TechnologyCenter in Esslingen-Berkheim in Germany, designed by the architect office of Ulrich Jaschek and completed in 2001 (Figure 5-65). The building features an atrium with a roof consisting of 3-layer ETFE foil cushions, with pneumatically adjustable sun screening. The outer and middle layer of the cushions have been printed with a positive and negative checkboard pattern, respectively. The middle foil layer can be adjusted pneumatically, to provide variable visible transmittance of 50-93 % (Figure 5-66). The cushions can also be humified in order to cool them down.



From [IntelligenteArchitektur **31**:35]

Figure 5-66: *The principle of pneumatically adjustible sun shading by means of ETFE foil cushions.*

An ETFE foil layer typically has a visible light transmittance of 94-97 %, and originally also transmits ultraviolet radiation. However, additional coatings can be provided to adjust the visible and solar transmittance of the foil. Similarly, the U-value of the cushions can be improved by means of low-E coatings, from its original value of 1.9 W / m^2K to 0.6 W / m^2K. Visual images are not retained due to the curvature of the material, and the cushions thus display a distorted view to the outdoor environment (Figure 5-67) [Robinson-Gayle *et al.* 2001; Tanno 1997].

[IntelligenteArchitektur **31**:35] © A.Braun, Hameln

Figure 5-67: *The ETFE foil cushions with* closed *and* open *solar shading (7 %, resp. 50 % visible light transmittance).*

Despite their much more limited range of application in the building envelope than the other examples discussed in this section, ETFE foil cushions have been selected for discussion because they represent a completely different form of adaptation of the building envelope, where the surface itself inflates/deflates to accommodate itself according to environmental changes. One could imagine to exploit this change in physical form further by means of amorphous photovoltaics, following the path of the sun, or by means of holographic optical films that redirect light into the atrium according to the varying incidence angle of daylight.

More information regarding the TechnologyCenter project may be obtained from the following sources:

- http://www.festo.com
- IntelligenteArchitektur **31**:29-41

6 General conclusions

How does an intelligent building envelope manage the variable and sometimes conflictive occupant requirements that arise in a daylit indoor environment?

This research question, introduced in Chapter 1, was answered in four steps:

- What characterises intelligent behaviour for a building envelope? (Chapter 2)
- What characterises indoor daylighting quality? (Chapter 3)
- Which functions can an intelligent building envelope be expected to perform in the context of daylighting quality? (Chapter 4)
- How are the materials, components and composition of an intelligent building envelope designed to influence this performance? (Chapter 5)

Chapter 6 summarises the answers to these questions, and evaluates the method used to obtain them. The research process has, furthermore, generated additional questions that could not be answered within the scope and time frame of this Ph.D. A third section lists these questions and recommendations for future research:

- Summary of findings
- Evaluation of the method used
- Recommendations for future research

6.1 Abstraction of findings

6.1.1 Characteristics of intelligent building envelopes

• **Intelligent vs. conventional building envelopes?** All building envelopes have the function of an environmental filter. What makes an intelligent building envelope stand out in its interaction with the environment? In the course of this dissertation, intelligent behaviour for a building envelope is defined as the ability to adapt to the environment consisting of the local climate and site, the building's functionality, and the individual building occupant. This adaptation occurs by means of perception, reasoning and action processes, and enables the envelope to cope with new situations and solve problems that may arise in its interaction with the environment. Thus, the envelope's performance as an environmental filter is extended with the ability to choose the most appropriate response in each situation, to make long-term strategies, to anticipate the development of environmental conditions, to evaluate its own performance, and the ability to learn. These characteristics intend to make the envelope more fit for performance in a particular environment, to extend its functionality, and to customise its operation to the individual user.

• **Active vs. passive design strategies?** Does an intelligent building envelope render superfluous the meticulous design of the building according to local climate and site? Most certainly not: active adaptation of the building envelope to its environment requires at least as much care and detailing as *passive* design strategies: the location of the components, their range of performance, their control and even their design need to be adjusted to the particular climate, site and building function. In all of the literature sources on adaptive materials, components, control algorithms and building envelopes examined in this study, the researchers, manufacturers and members of the design team stress the *importance* of designing this adaptation according to the local climate and site and to the functionality of the building for successful performance, and, simultaneously, the *difficulty* of achieving this.

• **Human vs. envelope intelligence?** Does the adjective *intelligent* mainly refer to the intelligent design and maintenance of the building envelope by humans, or can also an envelope's behaviour *in se* be qualified as intelligent? An intelligent building envelope is able to optimise, prioritise, anticipate, learn and remember in interaction with its environment, which are characteristics of intelligent behaviour. In order to perform successfully, however, this information processing capacity needs to be related to the design of the envelope components, their adaptivity and their composition in the building envelope. In addition, proper functioning of the building envelope requires co-operation of the maintenance and cleaning staff as well as of the building occupants, who need to know what the system is able to do, what it is supposed to do, and how to arrange the system's operation according to their individual needs.

6.1.2 Characteristics of indoor daylighting quality

Lighting quality, as defined by Veitch & Newsham, is *"the degree to which the luminous environment supports the following requirements of the people who will use the space: visual performance, post-visual performance, social interaction and communication, mood state, health and safety, and aesthetic judgements"* [1996a:10]; these requirements may also be applied to daylighting. Within the scope of this thesis, six conditions related to the luminous environment are selected for further discussion in the context of intelligent building envelopes:

- Luminous distribution
- Glare and veiling reflections
- Colour
- Directional properties
- Visual contact with the outdoor environment
- Individual control

6.1.3 Functional requirements: envelope intelligence for daylighting quality

The ability to adapt to changes in the environment by means of perception, reasoning and action helps an intelligent building envelope to handle the variable and sometimes conflictive requirements that arise in daylighting, and to optimise the indoor luminous environment to occupant requirements with an effective use of daylight resources.

- **Managing variability.** In theory, an intelligent building envelope is able to filter daylight's variability to a level that is desirable by the building occupant. When unacceptable variations are anticipated, their impact on the indoor luminous environment can be reduced, or the morphology of the envelope altered to use a different set of daylight sources. In practice, however, it is quite challenging for a building envelope to find out which daylight variations are desired by the building occupant. In addition, the envelope's response to the variations is strongly limited by the physical characteristics of its components. The applications discussed in Chapter 5 allow, in general, for only one or two types of adaptation with regard to material, form and composition, and their response to environmental changes is consequently dictated by the flexibility of the particular component rather than the specific adaptation required; this situation may change with the increasing development of nanotechnology and the design of components with made-to-measure adaptive characteristics. Furthermore, there exist considerable limitations with regard to the time frame for the envelope's response: limited information processing capacity may cause an unacceptable delay between perception and action, and the components that perform the action may need too much time to execute their response.

- **Managing conflicts.** In theory, an intelligent building envelope is able to optimise its response according to variable sets of performance criteria, featuring a range of response modes for different situations. In practice, the envelope's ability to solve conflicts and provide a response with a high leverage for all performance criteria is limited, on the one hand, spatially by the particular type of adaptation each of the envelope components is able to provide, and, on the other hand, temporally by the time needed to process all data and elaborate the most fit strategy; in order to quicken the envelope's response, less data or variables can be taken into account, which in turn limits the envelope's overview of the conflictive situation.

- **Managing occupant behaviour.** In theory, an intelligent building envelope is able to learn the occupants' needs and preferences so as to optimally adjust its response modes to their individual requirements instead of basing them on standard recommendations. In practice, this type of customisation is limited, first of all, by the divergence between the occupant's and the envelope's system of perception in location, detail, variability and, above all, brightness and chromatic adaptation. Thus, the envelope requires feedback from the building occupant in order to be able to customise the indoor luminous environment. In Chapter 5, different types of user-system interfaces are discussed for the manner in which they allow for communication between the envelope and the building occupant, amongst others by means of arrows, colours, graphs and numerical values. In addition, speech-based systems are under development, and interfaces are being equipped with fuzzy systems in order to convert imprecise user commands to a request the envelope is able to understand and insert into its information processing system. In order for this system to function appropriately, however, the occupant needs to be able to specify what she actually wants, and the envelope needs, as mentioned before, a flexible morphology that is able to provide the desired response.

• **Efficient use of available daylight sources.** In theory, the skills of an intelligent building envelope allow it to look for the most efficient manner in which to use the available daylight sources, with regard to their variability, accessibility and controllability. In practice, as mentioned earlier, this kind of functioning requires a flexibility of the envelope's perception and action system that is currently not available; in addition, the information processing capacity is not sufficient to achieve this type of strategy update in a real-time and on-line manner within a short time frame.

6.1.4 Physical application: envelope intelligence for daylighting quality

• **Self-sufficiency.** In Chapter 5, several applications were discussed where artificial intelligence is integrated into components for perception and action, a trend that is increasing as the development of information processing capacity is providing more customised solutions with a shorter response time. In addition, there seems to be a trend towards decentralisation of control systems in buildings, providing localised control in the building envelope instead of in a central core of the building. Combined with integrated photovoltaic systems, localised control options lead to an increasing degree of self-sufficiency for the building envelope.

• **Variety in design.** As mentioned earlier, it is not possible to reduce the intelligence of the building envelope to its information processing system; the design of the envelope's components and their composition in or co-operation with the envelope are at least as important. The selection of examples in Chapter 5 shows a myriad of manners in which to attend to specific daylighting functions, which can roughly be categorised into a limited number of groups such as Venetian blinds, external louvres, and switchable glazing. For each of those groups, however, a large number of parameters can be found that distinguishes one particular application from another as the design of these components' material characteristics and form, along with their location in the building envelope, to a variable degree have been adjusted to the local climate and site. In order to provide an appropriate response, the information processing system needs to be adjusted accordingly, not only to the particular type of components used, but also to the geometry and functionality of the indoor environment.

- **User-centered design.** This topic is partially discussed earlier, with regard to user-system interfaces and the manner in which the communication between envelope and occupant is organised. In addition, user interfaces may offer a flexible degree of control according to the occupant's wishes, with the possibility to influence the situation state and/or the control state in a general or more detailed manner according to circumstances. The communication between envelope and occupant should, however, be extended to the design and operation of envelope components and the visualisation of their adaptiveness, in order for the occupant to clearly understand why the envelope responds in the manner it does, the range of responses possible given the particular envelope morphology, and the manner in which the occupant can influence them.

- **Integrated design.** Does the architect decide upon the visual expression of the envelope for the engineer afterwards to design its operation and automation? Or does an intelligent building envelope consist of components designed for integration and close co-operation? How can the visual expression of the envelope and its operation be tuned to reach points of high leverage? Several examples discussed in Chapter 5 are the result of a close co-operation between the design team of a building and manufacturers of lighting and shading systems, often over a longer period of time rather than being limited to one building project. The components used in those examples are not taken *off the shelf* and made to co-operate in the building envelope; on the contrary, they are designed for use in close co-operation (in multi-layered solutions) or even integration (in multifunctional components) with other envelope components to perform daylighting, shading and artificial lighting functions, and adjusted to the particular climate, site and building they are going to be applied in. Integrated design is not limited to the envelope itself; there is a clear trend towards an *extended* building envelope, that uses all resources available, and *outsources* the performance of functions to the location and device that is assumed to provide the best service.

6.2 Evaluation of the method used

Systems analysis was chosen as a method to identify the different levels in the operation of an intelligent building envelope, and evaluate their performance with regard to a chosen target: daylighting quality. Analysing the envelope as a system was expected to contribute in the identification of the different missions the envelope needs to perform, describe the relations that exist between them, and evaluate the consequences of choosing particular physical components to perform those functions.

6.2.1 Defining an intelligent building envelope

- **An operational definition.** An operational definition does not automatically link an intelligent building envelope to the achievement of specific goals, but rather depicts the skills and behaviour to be expected from an intelligent building envelope in order to attain those goals. Working with an operational definition of intelligent building envelopes has made it possible to relate *intelligence*, above all, to the behaviour of the building envelope rather than its intelligent design by humans or even its visual expression, and to evaluate the contribution of particular materials, components and composition to an appropriate functioning of the building envelope.

- **The use of literature sources.** A first review of literature in architecture and building design did not reveal sufficient information regarding behavioural characteristics for an intelligent building envelope. Therefore, expert literature in psychology on the development of intelligent behaviour in humans was consulted, a range of elementary characteristics of intelligent behaviour abstracted, and the relevance of their transfer to intelligent building envelopes evaluated by comparison with definitions of intelligent systems in building design, control systems and artificial intelligence. The best correspondence was found in the field of artificial intelligence, which is not surprising as artificial intelligence is a field of computer science that attempts to mimick the functioning of the human brain.

- **Model: human intelligent behaviour.** The use of psychical processes that procure intelligent behaviour in humans as a basis for the operation of an intelligent building envelope has proven to be successful. From expert literature in psychology, the ability to adapt to the environment by means of perception, reasoning and action was abstracted as an elementary characteristic for intelligent behaviour, and this result transferred to the operation of the building envelope. It is clear that this transfer is possible for a limited selection of intelligence characteristics only, as features such as *creativity* and *Aha-Erlebnis* are, with current technology, not obtainable by a building envelope. While this type of approach helps to describe the functioning of an intelligent building envelope, it might simultaneously be misinterpreted as a reduction of the concept of intelligent building envelopes to the use of artificial intelligence and the automation of components and functions. Thus, it becomes important to show how the architectural design of the envelope is crucial for an appropriate functioning of the artificial intelligence.

6.2.2 Describing daylighting quality

- **Current state-of-the-art.** The list of functions an intelligent building envelope can be expected to provide with regard to daylighting quality, developed in Chapter 4, is based on the current state-of-the-art research in daylighting. However, knowledge regarding the influence of the luminous environment on humans is not complete, and new information may appear which calls for some of the functions to be altered or replaced. While a wide range of conditions in the luminous environment have been identified to contribute to good daylighting quality, there appears to be no agreement on the relative importance of each of these conditions, nor on the manner in which they affect each other. One such example is the importance of retinal illuminance for circadian rhythm, which may come to require a different course of action on the envelope's behalf. In addition, there is inconsistent knowledge on the manner in which building occupants react to control by the building envelope, which may be discovered to severely interfere with daylighting quality, causing for some of the functions to be altered or exchanged.

6.2.3 Functional analysis: envelope intelligence for daylighting quality

- **A distinction between tasks and devices.** Was it fruitful to distinguish between an analysis of functions and an analysis of physical applications? This question has already partially been answered in the abstraction of findings. In theory, there is a wide range of functions an intelligent building envelope can be expected to perform in order to influence and improve indoor daylighting quality and provide an indoor luminous environment according to the user's requirements. In choosing a particular physical application to fulfil those functions, however, the envelope becomes limited in its response to variations and conflicts according to the physical characteristics of the envelope components. In addition, the envelope's information processing capacity is limited in its ability to optimise and prioritise with regard to the number of parameters, the frequency of data analysis, and the response time between perception and action. Analysing functions before to evaluate the efficiency of components in performing them, has helped to assess the range of materials, components and building envelopes identified in literature and to evaluate their shortcomings and benefits. A distinction between tasks and devices clarifies the different manners in which an envelope is able to respond to environmental conditions, simplifies the identification of consequence patterns a particular choice of physical application generates, and helps to assess how a particular function could be performed in a more effective manner.

- **A wide range of functions.** The wide range of functions an intelligent building envelope can be expected to perform in order to influence and improve indoor daylighting quality, described in Chapter 4, is the result of a systematic analysis of combinations between envelope skills on the one hand, and conditions related to the indoor luminous environment on the other hand, aiming to create an exhaustive range of performance criteria that can be used to assess the potential of each physical application selected in Chapter 5. Therefore, it needs to be interpreted as a list of options rather than demands, and by no means is there an expectation that one application is able to fulfil all of the criteria listed in Chapter 4.

6.2.4 Physical application: envelope intelligence for daylighting quality

Was is fruitful to use literature sources to identify, analyse and evaluate physical applications for an intelligent building envelope?

- **Different levels of application.** The mixture of literature sources used for Chapter 5 identified physical applications on two levels: a micro-level consisting of individual materials and components that can be applied in an intelligent building envelope - some of them not being commercially available yet - and the research that is being conducted in order to optimise their design and operation; on the other hand, a meso-level consisting of building examples, where the envelope is the product of a compromise between architects', engineers', building owners' and occupants' demands and its operation subjected to a given range of priorities and limitations in confrontation with a real-time environment.

- **Insufficient information.** The literature sources did not always provide sufficient information in order to analyse the performance of the physical applications according to the list of functions elaborated in Chapter 4. These gaps have been filled by contacting the researchers, members of the design team, and manufacturers, and asking them specific questions. In general, the response was positive and most of the people contacted, willingly provided the additional information as requested.

- **Performance assessment.** The approach chosen for this Ph.D. made it possible to discuss a wide range of potential solutions, and map several alternatives. However, it has clear limitations in the assessment of their performance. The analysis of each application is descriptive and evaluates the potential and shortcomings of each element, however, there is no measurement of performance or other quantitative results that are easily compared.

- **The selection of applications.** The choice to evaluate a large number of physical applications rather than discussing two or three case studies, in this particular study, brought to the attention several examples that otherwise are not ostentively applying for a description as *intelligent* building envelope. It is tempting to look for building envelopes with clearly distinctive characteristics, such as moveable components and a visualised adaptation of the building envelope. For some of the examples discussed in Chapter 5, adaptation is achieved by means of the integrated design of various components in the building envelope, but this adaptation is not instantly noticeable in the visual expression of the envelope. On the other hand, the description of these examples may have become more general as compared to an in-depth case study of two or three buildings supplied with in-situ measurements or interviews with the design team, manufacturers, building owners and users in order to evaluate the envelope's performance.

6.3 Recommendations for future research

6.3.1 The design and operation of an intelligent building envelope

The concept of intelligent building envelopes touches on a variety of topics that deserve further exploration. From an architectural point of view, it is intriguing to explore how the design and operation of an intelligent building envelope carries consequences for various user groups, for the functionality of the indoor environment and for different aspects of indoor climate, and, consequently, to analyse how the design and operation of the envelope need to be adjusted in order to obtain the desired effect.

- **The optimisation of communication between envelope and occupant.** How do building occupants experience the control an intelligent building envelope exercises over the indoor environment? How do occupants use the control options they are given? How can the design of interfaces be optimised for this type of application?

- **The optimisation of the adaptiveness of the building envelope.** What kind of flexibility is desirable for envelope morphology in order to use the available daylight sources more efficiently? Is it possible and fruitful for the envelope to use resources to identify the most appropriate daylight sources in its environment and adjust its operation accordingly?

- **The optimisation of daylighting in confrontation with other envelope functions.** How can the envelope's daylighting strategies successfully be combined with strategies for natural ventilation, cooling, heating and the production of electricity? How can the design and operation of components be adjusted to not only avoid conflicts between functions, but even to mutually enhance each other's outcome?

6.3.2 Additional user groups

Apart from the building occupant, there are several user groups that deserve additional focus, such as:

- **Building owners.** What is their gain when deciding to opt for this type of building envelope? What can be achieved for a certain amount of money? This is not only related to capital and operational cost, but also to features such as image, functionality and flexibility.

- **Maintenance staff.** What is the nature and frequency of maintenance required? Are the components easily accessible, and does their maintenance require additional training of the staff? An intelligent building envelope may be able to diagnose and even repair its own malfunction, but, on the other hand, building occupants may need special training and assistance to deal with this kind of building envelope.

- **Design team.** What are the premises for a design team to opt for an intelligent building envelope? Is this wish forwarded by the client or by the team itself? How does such a design process proceed in practice? What are the incentives? What is the outcome? Is the team learning, building up experience to be invested in the next project?

6.3.3 Additional building types

In addition to offices, other building types may gain from the application of an intelligent building envelope. How can the design and operation of an intelligent building envelope be extended to other building types? For each type of building, one needs to define the level of service that is to be acquired according to the building program and the tasks and activities of the users. With regard to daylighting quality, for example, the following challenges may arise:

- **Classrooms.** As daylight is indicated to influence alertness, social interaction and productivity by means of the circadian system, it may prove to be advantageous to provide flexible daylighting for group and individual activities that occur in a classroom throughout the day and year. Daylighting conditions would, however, need to be optimised for multiple occupants simultaneously.

- **Health care facilities.** As daylight and a view to the outdoor environment have a beneficent effect on health, this may be used to the advantage of health care facilities. The visual field of the average patient, however, is quite different from that of an office worker, as the former tends to recline most of the day, with a low acitivity level. In addition, several patients might share a room, multiplying the challenges posed to optimising light redirection, glare protection, view, enclosure and privacy.

- **Residential buildings.** Some of the issues discussed in this thesis would also be applicable to residential buildings; however, such an operating environment may be less demanding, as the occupant enjoys a larger mobility within the residence, rather than being stuck in certain workplace the entire time. In addition, the costs are probably too large, given the lesser urgency of actively controlling daylighting quality in a residential building. With a more blurry boundary between work and residential environment and more people working at home, however, the functionality of the home, and thus the challenges posed to the building envelope, may need to be extended.

6.4 Concluding remarks

Is this one of those so-called intelligent facades?

A question often heard once people know this is your topic of research. The answer, however, is not as self-evident as one might want it to be. The intelligence of a building envelope can not be derived from its visual expression or the use of moveable components. Intelligence rather needs to be related to the level of service the envelope is required to provide: the ability to adjust its operation according to variable and sometimes conflicting demands, and the knowledge to do so with an appropriate timing.

The use of adaptive solutions and an extended functionality and flexibility of the building envelope, however, in no manner reduces the need for meticulous design according to the local climate and site, the functionality of the building, and the quality of the indoor environment. In all of the sources that were consulted during the course of this Ph.D., it is time and time again stressed how *difficult* it is to control the operation of the envelope components according to the local environment, and, simultaneously, how *important* it is to do so.

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Glossary

The definitions have been copied from the following sources:

[a] CIE Vocabulary, in Baker, N.; Fanchiotti, A.; Steemers, K. (ed.) (1993). *Daylighting in architecture - a European reference book*. The Commission of the European Communities, Directorate General XII for Science Research and Development. London: James & James (Science Publishers) Ltd. GL.2-9.

[b] CEC Vocabulary, in Baker, N.; Fanchiotti, A.; Steemers, K. (ed.) (1993). *Daylighting in architecture - a European reference book*. The Commission of the European Communities, Directorate General XII for Science Research and Development. London: James & James (Science Publishers) Ltd. GL.10-34.

Absorption. Process by which radiant energy is converted to a different form of energy by interaction with matter. [a]

Adaptation. The process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminances, spectral distributions and angular subtenses. [a]

Angle of incidence. The angle between a ray of light falling on a surface and a line perpendicular to the surface. [a]

Atrium. An interior light space enclosed laterally by the walls of a building and covered with transparent or translucent material which permits the entry of light to the other interior spaces linked to it. [b]

Blind. An exterior or interior element composed of slatted screens placed the whole of a window. The slats may be fixed or moveable. When moveable it may be adjusted according to sun angle and shading requirements. This device can be moved along the opening, drawn to the side, or rolled up to the top. [b]

Bright. Adjective used to describe high levels of brightness. [a]

Brightness. Attribute of a visual sensation according to which an area appears to emit more or less light. [a]

Colour rendering. Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant. [a]

Colour rendering index. (R) Measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation. [a]

Colour temperature. (T_c) The temperature of a Planckian radiator whose radiation has the same chromacity as that of a given stimulus. [a]

Contrast. (1) In the perceptual sense: Assessment of the difference in appearance of two or more parts of a field seen simultaneously or successively (hence: *brightness contrast, lightness contrast, colour contrast, simultaneous contrast, successive contrast,* etc.); (2) In the physical sense: Quantity intended to correlate wiht the perceived brightness contrast, usually defined by one of a number of formulae which involve the luminances of the stimuli considered, for example: $\Delta L / L$ near the luminance threshold, or L_1 / L_2 for much higher luminances. [a]

Daylight. Visible part of global solar radiation. [a]

Daylight opening; aperture. Area, glazed or unglazed, that is capable of admitting daylight to an interior. [a]

Diffused lighting. Lighting in which the light on the working plane or on an object is not incident predominantly from a particular direction. [a]

Diffuse reflection. Diffusion by reflection in which, on the macroscopic scale, there is no regular reflection. [a]

Diffuse sky radiation. That part of solar radiation which reaches the Earth as a result of being scattered by the air molecules, aerosol particles, cloud particles or other particles. [a]

Diffuse transmission. Diffusion by transmission in which, on the macroscopic scale, there is no regular transmission. [a]

Diffusion; scattering. Process by which the spatial distribution of a beam of radiation is changed when it is deviated in many directions by a surface or by a medium, without change of frequeny of its monochromatic components. [a]

Direct glare. Glare caused by self-luminous objects situated in the visual field, especially near the line of sight. [a]

Directional lighting. Lighting in which the light on the working plane or on an object is incident predominantly from a particular direction. [a]

Direct solar radiation. That part of extraterrestrial solar adiation which as a collimated beam reaches the Earth's surface after selective attenuation by the atmosphere. [a]

Direct sunlight. Portion of daylighting coming directly from the sun at a specific location which is not diffused on arrival. [b]

Disability glare. Glare that impairs the vision of objects without necessarily causing discomfort. [a]

Discomfort glare. Glare that causes discomfort without necessarily impairing the vision of objects. [a]

Electromagnetic radiation. Emission or transfer of energy in the form of electromagnetic waves with the associated photons. [a]

Glare. Condition of vision in which tere is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts. [a]

Illuminance. (at a point of a surface) (E_v; E) Quotient of the luminous flux $d\Phi_v$ incident on an element of the surface containing the point, by the area dA of that element. [a]

Indirect lighting. Lighting achieved by reflection, usually from wall and/or ceiling surfaces. [b]

Interreflection. General effect of the reflections of radiation between several reflecting surfaces. [a]

Irradiance. (at a point of a surface) (E_e; E) Quotient of the radiant flux $d\Phi_e$ incident on an element of the surface containing the point, by the area dA of that element. [a]

Light. (1) Perceived light; (2) Visible radiation. [a]

Lighting; illumination. Application of light to a scene or their surroundings so that they may be seen. (Note: This term is also used colloquially with the meaning “lighting system” or “lighting installation”). [a]

Lumen. (lm) SI unit of luminous flux: Luminous flux emitted in unit solide angle (steradian) by a uniform point source having a luminous intensity of 1 candela. [a]

Luminance. (in a given direction, at a given point of a real or imaginary surface) (L_v; L) Quantity defined by the formula $L_v = (d\Phi_v) / (dA * \cos\theta * d\Omega)$, where $d\Phi_v$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam; Unit: $cd * m^{-2} = lm * m^{-2} * sr^{-1}$. [a]

Luminous efficacy of radiation. (K) Quotient of the luminous flux Φ_v by the corresponding radiant flux Φ_e; $K = \Phi_v / \Phi_e$ (Unit: $lm * W^{-1}$). [a]

Luminous environment. Lighting considered in relation to its physiological and psychological effects. [a]

Obstruction. Anything outside a building which prevents the direct view of part of the sky. [a]

Opaque medium. Medium which transmits no radiation in the spectral range of interest. [a]

Perceived light. Universal and essential attribute of all perceptions and sensations that are peculiar to the visual system. [a]

Permanent supplementary artificial lighting. (in interiors) Permanent artificial lighting intended to supplement the natural lighting of premises, when the natural lighting is insufficient or objectionable if used alone. (Note: This type of lighting is generally denoted in brief by the initial letters PSALI of the words of the English term). [a]

Reflectance. (for incident radiation of given spectral composition, polarisation and geometrical distribution) (ρ) Ratio of the reflected radiant or luminous flux to the incident flux in the given conditions. [a]

Reflected glare. Glare produced by reflections, particularly when the reflected images appear in the same or nearly the same direction as the object viewed. [a]

Reflection. Process by which radiation is returned by a surface or a medium, without change of frequency of its monochromatic components. [a]

Regular reflection; specular reflection. Reflection in accordance with the lays of geometrical optics, without diffusion. [a]

Regular transmission; direct transmission. Transmission in accordance with the laws of geometrical optics, without diffusion. [a]

Shading. Device designed to obstruct, reduce or diffuse solar radiation. [a]

Skylight. Visible part of diffuse sky radiation. [a]

Solar radiation. Electromagnetic radiation from the sun. [a]

Sunlight. Visible part of direct solar radiation. [a]

Translucent medium. Medium which transmits visible radiation largely by diffuse transmission , so that objects are not seen distinctly through it. [a]

Transmission. Passage of radiation through a medium without change of frequency of its monochromatic components. [a]

Transmittance. (for incident radiation of given spectral composition, polarisation and geometrical distribution) (τ) Ratio of the transmitted radiant or luminous flux to the incident flux in the given conditions. [a]

Transparent medium. Medium in which the transmission is mainly regular and which usually has a high regular transmittance in the spectral range of interest. (Note: Objects may be seen distinctly through a medium which is transparent in the visible region, if the geometric form of the medium is suitable). [a]

Veiling reflections. Specular reflections that appear on the object viewed and that partially or wholly obscure the details by reducing contrast. [a]

Visible radiation. Any optical radiation capable of causing a visual sensation directly. (Note: There are not precise limits for the spectral range of visible radiation since they depend upon the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 nm and 400 nm and the upper limit between 760 nm and 830 nm.) [a]

Visual performance. Performance of the visual system as measured for instance by the speed and accuracy with which a visual task is performed. [a]

Work plane; working plane. Reference surface defined as the plane at which work is usually done. [a]

Summary

How does an intelligent building envelope manage the variable and sometimes conflictive occupant requirements that arise in a daylit indoor environment?

This is the research question that provides the basis for this Ph.D. work. As it touches upon several fields of application, the research question is untangled into four steps, each of which corresponds to a chapter of the thesis (Figure 1).

1. What characterises intelligent behaviour for a building envelope? (Chapter 2)
2. What characterises indoor daylighting quality? (Chapter 3)
3. Which functions can an intelligent building envelope be expected to perform in the context of daylighting quality? (Chapter 4)
4. How are the materials, components and composition of an intelligent building envelope designed to influence this performance? (Chapter 5)

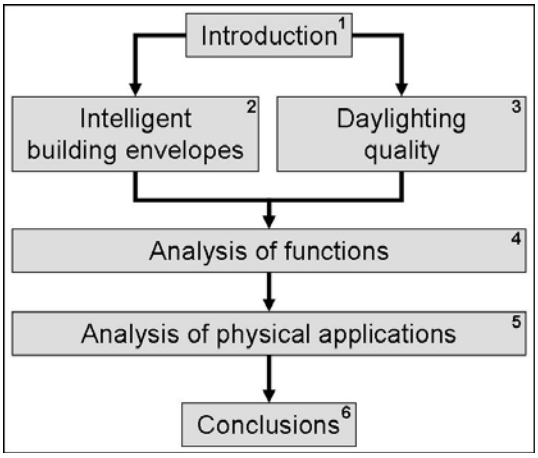

Figure 1: *The structure of the research strategy applied in this thesis.*

The first question concerns the distinctive qualities of an intelligent building envelope: all building envelopes function as an environmental filter; what makes an intelligent building envelope stand out in its interaction with the environment?

The second, third and fourth questions are related to the service that can be expected from an intelligent building envelope with regard to daylighting quality. The envelope's collection, admission and distribution of daylight indoors determines its successfulness in creating an appealing indoor luminous environment with an effective use of daylight sources. Which functions does the building envelope need to perform, and how does its *intelligence* influence the performance of those functions? When are these particular characteristics fruitful for daylighting quality?

Method

- **A systems approach**

What does an intelligent building envelope do? Which tasks related to daylighting quality does it need to fulfil? And which devices can be deployed to perform exactly that task? In order to evaluate an intelligent building envelope's performance with regard to daylighting quality, the envelope is described as a system or "a set of interrelated and interacting component parts that, when put together, function to achieve a predetermined goal or objective" [Fitzgerald & Fitzgerald 1987:10]. The different missions the envelope needs to perform are analysed, the relations that exist betweem them are described, and the consequences of choosing a particular physical component to perform those functions are evaluated.

- **An operational definition for intelligent building envelopes**

Within the scope of this thesis, it is chosen to work with an operational definition that does not primarily link an intelligent building envelope to the achievement of specific goals or the use of particular components, but rather depicts the *intelligent behaviour* that can be expected from the envelope in order to attain those goals.

As a basis for the definition of envelope intelligence, the physicological development of *intelligence in humans* is explored. The main characteristic is the *adaptiveness* of the subject to its environment, by means of psychical processes of *perception*, *reasoning* and *action*, allowing the subject to deal with new situations and to solve problems that may occur when interacting with the environment.

- **Characterising daylighting quality**

It is then analysed how an intelligent building envelope can use these processes to collect, admit and distribute daylight indoors and create a desirable indoor luminous environment. In this context, daylighting quality is defined as *"the degree to which the luminous environment supports the following requirements of the people who will use the space: visual performance, post-visual performance, social interaction and communication, mood state, health and safety, and aesthetic judgements"* [Veitch & Newsham 1996a:10]. Six conditions related to the luminous environment are selected for further discussion in the context of intelligent building envelopes:

- Luminous distribution
- Glare and veiling reflections
- Colour
- Directional properties
- Visual contact with the outdoor environment
- Individual control

- **Systems approach: a distinction between tasks and devices**

The functions a building envelope needs to perform in the context of daylighting quality are variable and sometimes conflictive. Therefore, one needs to distinguish between conflicts that appear within this functionality, and those that appear because of the physical components and materials that are chosen to execute those functions. As a consequence, there is a strict distinction in the thesis between a functional analysis of the envelope's tasks related to daylighting quality, and an analysis of the physical elements that may be deployed to perform those tasks.

- **Functional analysis**

In order to analyse the functions an intelligent building envelope can perform in the context of daylighting quality, the three characteristics intrinsic to envelope behaviour - *perception*, *reasoning* and *action* - are interrelated with the six conditions contributing to daylighting quality, as shown in Figure 2. Each of the matrix fields is analysed in a systemic pattern, and conflicts and opportunities are identified.

	Perception	Reasoning	Action
Luminous distribution			
Glare & veiling reflections			
Colour			
Directional properties			
Contact with outdoor environment			
Individual control			

Figure 2: *A matrix of interrelations between intelligent envelope behaviour and conditions in the luminous environment that are found to contribute to daylighting quality.*

- **Physical application**

A selection of physical applications is discussed for their potential to support the kind of functionality that is expected of an intelligent building envelope with regard to daylighting quality. In theory, a wide range of functions can be performed in order to provide an indoor luminous environment according to the user's requirements. In practice, however, the envelope's response to variations and conflicts becomes limited due to the physical characteristics of the envelope components and the capacity of its information processing system. In this thesis, consequence patterns generated by the use of each particular application are identified and evaluated for the nature and extent of functionality provided, and for the manner in which conflictive requirements are handled. Strengths and weaknesses are assessed, and suggestions for increased adaptiveness are made.

- **The use of literature sources**

Within the scope of this thesis, it is chosen to work with literature sources, supplied with information provided by contact with the members of the design team and manufacturers. The information obtained in this manner is expected to expose the diversity that exists within the concept of intelligent building envelopes, and the variety of applications that can be found in the design and operation of intelligent building envelopes with regard to daylighting quality. Two main sources are used for the collection of material, each of them offering a different perspective:

- ***Research papers.*** This source typically discusses particular solutions to meticulously defined problems, and thus constitutes a deliberate and separate study of the research field itself. Scientific papers are selected from the Science Direct online database, comprising all magazines published by Elsevier Science Ltd.

- ***Architectural magazines.*** This source explores how research and building practice join forces to create an architectural solution in a real-time environment, either by developing new products, in co-operation with the architect or design team, or by adaptating existing products to a concrete site, function and climate. In this context, the main literature source for this thesis is the German magazine *Intelligente Architektur*, published by Alexander Koch GmbH.

Findings

- **Intelligent building envelopes**

During the past few decades, buildings have been imposed to steadily extend their functionality at diminishing cost. Increasingly varying and complex demands related to user comfort, energy and cost efficiency have lead to an extensive use of mechanical systems to create a satisfactory indoor climate. The expanding application of control technology in this context has lead to the emergence of the terms *intelligent building* and *intelligent building envelope* to describe a built form that can meet such demands, be it to a varying degree of success. A multitude of definitions of intelligent building envelopes, however, opens for divergent interpretations of the design, operation and objectives of this type of envelope.

Within the scope of this research, an intelligent behaviour for a building envelope is defined as *adaptiveness* to the environment by means of psychical processes of *perception*, *reasoning* and *action*, which enables the envelope to solve conflicts and deal with new situations that occur in its interaction with the environment. Among the characteristics discussed in this thesis, are the envelope's ability to choose the most appropriate response in each situation, to make long-term strategies, to anticipate the development of environmental conditions, to evaluate its own performance, and the ability to learn. These characteristics extend the envelope's functionality, and allow it to customise its operation to the individual user.

In order to perform successfully, however, the envelope's reasoning capacity needs to be related to the design of the envelope components, their adaptivity and their composition in the building envelope. In addition, proper functioning of the building envelope requires the co-operation of the maintenance staff and the building occupants, who need to know what the system is able to do, what it is supposed to do, and how to arrange the system's operation according to their individual needs.

- **Indoor daylighting quality**

Proper daylighting strategies always start with architectural design adapted to local climate and site, and to the specific function of the building; this can be modelled in the design phase and then incorporated in the form and material use of the building. In a real-time environment, however, daylighting poses a range of variable and sometimes conflictive requirements related to occupant comfort and energy use, the nature and extent of which are difficult to predict and model on beforehand.

Does an intelligent building envelope render superfluous the meticulous design of the building according to local climate and site? Most certainly not: active adaptation of the building envelope to its environment requires at least as much care and detailing as *passive* design strategies; the design and location of the components, their range of performance, and their control need to be adjusted to climate, site and building function. For all of the adaptive materials, components, control algorithms and building envelopes examined in this study, the researchers, manufacturers and members of the design team stress the *importance* of designing this adaptation according to the local climate and site and to the functionality of the building for successful performance, and, simultaneously, the *difficulty* of achieving this.

- **Functional requirements: envelope intelligence for daylighting quality**

Does the ability to adapt to the environment by means of perception, reasoning and action, help an intelligent building envelope to handle the variable and sometimes conflictive requirements that arise in daylighting, and to optimise the luminous environment to occupant requirements with an effective use of daylight resources?

• ***Managing variability.*** Daylight is a highly variable light source in intensity, spectral distribution and directionality. In theory, an intelligent building envelope is able to filter daylight's variability to a level that is desirable for the occupant, either by reducing daylight's impact on the indoor environment, or by choosing a different set of daylight sources. In practice, however, it is challenging for the envelope to find out which daylight variations are desired by the occupant. Among the applications discussed in this thesis, the envelope's response to variations seems to be dictated by the flexibility of envelope components rather than by the specific adaptation required; this may change with the development of nanotechnology and the design of components with made-to-measure adaptive characteristics. Furthermore, there exist considerable limitations with regard to the time frame for the envelope's response: limited information processing capacity may create an unacceptable delay in response, and cause irritation among the building occupants.

• ***Managing conflicts.*** The envelope meets variable and conflictive demands of transparency versus privacy, of openness versus insulation, of access to daylight versus solar shading. In theory, an intelligent building envelope can optimise its response to variable sets of performance criteria, featuring a range of response modes for different cases. In practice, the envelope's ability to solve conflicts and optimise its response for all performance criteria is limited, on the one hand, by the particular type of adaptation each of the envelope components is able to provide, and, on the other hand, by the time needed to process all data and elaborate the most fit strategy. In order to quicken the envelope's response, less data or variables can be taken into account, which in turn limits the envelope's overview of the conflict.

• ***Managing occupant behaviour.*** Occupant requirements for transparency and daylighting vary with individual, cultural and functional needs and preferences. In theory, an intelligent building envelope can learn occupant needs and preferences and adjust its response to their individual requirements instead of basing them on standard recommendations. In practice, this customisation is limited, first of all, by the divergence between the occupant's and the envelope's perception system in location, detail, variability, and brightness and chromatic adaptation. Therefore, customisation of the indoor luminous environment requires feedback from the occupant. In this thesis, user-system interfaces are discussed for the manner in which they allow for communication between envelope and occupant, amongst others by means of arrows, colours, graphs and numerical values. In addition, speech-based systems are under development, and interfaces are being equipped with fuzzy systems in order to convert imprecise user commands to a request the envelope is able to understand and process. In addition, however, the occupants need to be able to specify their actual needs, and the envelope needs, as mentioned before, a flexible morphology that is able to provide the desired response.

• ***Efficient use of available daylight sources.*** In addition to providing a desirable indoor luminous environment, the envelope needs to use the available lumens effectively, in order to avoid undesirable solar heat gain. In theory, an intelligent building envelope can assess the variability, accessibility and controllability of the available daylight sources and choose the most appopriate one. In practice, this skill requires a flexibility of the envelope's perception and action system that is currently not available; in addition, the envelope's information processing capacity is not sufficient to provide this service in direct interaction with its environment.

- **Physical application: envelope intelligence for daylighting quality**

• ***Self-sufficiency.*** In this thesis, several applications are discussed where artificial intelligence is integrated into components for perception and action, a trend that is increasing as the development of information processing capacity is providing more customised solutions with a shorter response time. In addition, there seems to be a trend towards the decentralisation of control systems in buildings, providing localised control in the building envelope instead of in a central core of the building. Combined with integrated photovoltaic systems, localised control options lead to an increasing degree of self-sufficiency for the building envelope.

• ***Variety in design.*** The intelligence of the building envelope can not be reduced to its information processing system; the design of envelope components and their composition in or co-operation with the envelope are at least as important. The examples selected for this thesis represent a myriad of manners in which to attend to specific daylighting functions by means of components' material characteristics and form and their location in the building envelope, adjusted to local climate and site. In order to provide an appropriate response, the information processing system needs to be adjusted accordingly, not only to the particular type of components used, but also to the geometry and functionality of the indoor environment.

• ***User-centered design.*** In addition to organising communication between envelope and occupant, user-system interfaces can be designed to offer a flexible degree of control according to the occupant's wishes. The communication between envelope and occupant should also be extended to the design and operation of envelope components and the visualisation of their adaptiveness, in order for the occupant to clearly understand why the envelope responds in the manner it does, the range of responses possible given the particular envelope morphology, and the manner in which the occupant can influence them.

• ***Integrated design.*** Several examples in this thesis are the result of close co-operation between a building's design team and the manufacturers of daylighting systems, often extending beyond the limit of a specific building project. The components used in those cases are not taken *off the shelf* and made to co-operate in the envelope; on the contrary, they are designed for use in close co-operation (multi-layered solutions) or integration (multifunctional components) with other envelope components to perform daylighting, shading and artificial lighting functions, and adjusted to the climate, site and building they are going to be applied in. In addition, integrated design is not limited to the envelope itself; there is a clear trend towards an *extended* building envelope, that uses all resources available, and *outsources* the performance of functions to the location and device that provides the best service.

Concluding remarks

Is this one of those so-called intelligent facades?

A question often heard once people know this is your research topic. The answer, however, is not as self-evident as one might think. The intelligence of a building envelope can not be derived from its visual expression or the use of moveable components. Intelligence rather needs to be related to the level of service the envelope provides: the ability to adjust its operation according to variable and sometimes conflicting demands, and the knowledge to do so with appropriate timing.

The use of adaptive solutions and an extended functionality and flexibility of the building envelope, however, in no manner reduces the need for meticulous design according to local climate and site, building program, and the quality of the indoor environment. All of the sources consulted during the course of this Ph.D. stress time and time again how *difficult* it is to control the operation of the envelope components according to the local environment, and, simultaneously, how *important* it is to do so.