A Multi-Criteria Decision-Making Method for Solar Building Design

by

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Foreword

Utilization of solar energy in buildings have been my main professional interest and field of work since I got my Masters' degree in Building Energy Systems at the University of Colorado in 1991. During the years prior to my Ph.D. work I have done numerous computer simulations and investigations of building integrated solar energy systems in order to evaluate their energy efficiency and cost-effectiveness. I have also had the pleasure to see different types of solar systems slowly emerging from more or less stand-alone systems to becoming really integrated parts of the building. In particular, facade-integrated photovoltaic systems have had an incredible progress during these years, especially for office buildings. Also, many different types of active and passive solar thermal strategies, as well as daylighting systems are interesting for future office buildings. Solar facades of office buildings have to fulfill a wide range of criteria. They should not only be energy- and cost-efficient, they should also provide comfort, be "environmentally friendly", have a nice appearance, etc.

Looking at the wide range of different solar systems for integration into facades, the following question appeared interesting: What would be the optimal combination of systems and integration strategies for utilization of solar energy in an office building, given certain constraints? The clue was to find systems that would not only be optimal with respect to energy and economy, but also with respect to other important design issues, such as comfort, environmental loading and aesthetics. Therefore, the initial scope for this thesis was to search for a strategy or a combination of strategies that would best fulfill all these criteria. However, as I started to really define the work of the thesis, I realized that there could never be such a thing as an optimal building integrated solar energy system. So many things are different from project to project, and moreover, the preferences of the clients and other decision-makers cannot be generalized. Therefore, my strategy changed from that of technical optimization to finding a strategy of how to account for all the different optimization criteria and preferences.

This viewpoint led me into fields of expertise that had so far been quite unknown to me. I have investigated strategies from fields ranging from behavioral sciences, psycho-physics, and management science to design theory and economics. The challenge was to combine the theories of these fields with my knowledge of solar building design, and apply it to the task of the thesis. As such, I felt that my work was deviating quite a lot from the conventional doctoral thesis, i.e. having a much wider

profile. I must say that the work has not been very streamlined, and quite demanding, but definitely very interesting and fun.

I wish to express my gratitude to my advisor, Professor Anne Grete Hestnes, for giving me the perfect amount of guidance and freedom during my study.

Special thanks go to Professor Øyvin Skarstein, who guided me into the field of decision analysis and helped me come through it with great joy and pleasure. Without him, this thesis would probably have been quite different, and I believe that doing my work would have been much less fascinating.

Also, thanks are due to Professor Øyvind Aschehoug, for trying to keep me down to earth, and for making it all possible by arranging the financial support.

During my Ph.D. work I was fortunate to be involved in two international projects that dealt with related topics. One was the EU project *Amorphous Silicon Photovoltaic in Commercial Buildings*, where I was involved in the work within subtask *4.1: Optimization and Trade-Off*. The financial support for participation in this project, as well as for the entire Ph.D. work was provided by Hydro Aluminum Metal Products (HAMP). I wish to express my gratitude to HAMP, and especially to Mr. Einar Wathne, for giving me this opportunity and for taking such good care of Ph.D. students. The other project was the IEA Solar Heating and Cooling Programme, Task 23: *Optimization of Solar Energy Use in Large Buildings*. In this project I was mainly involved in subtask *C3: Methods and Tools for Trade-Off Analysis*. My appreciation goes to all the participants of this project who provided constructive feedback and interesting discussions that were useful for my work. Special thanks go to Dr. Doug Balcomb of NREL, Colorado, to Pekka Houvila of VTT, Helsinki, and to Mr. Nils Larsson of CANMET, Ottawa, for useful discussions and information exchange. Finally, thanks are due to Anne Grete Hestnes for giving me the opportunity to participate in these projects, thus taking me out of the office into an interesting international arena.

I would also like to thank the willing participants of my case studies, especially Mr. Per Monsen of GASA, Oslo, Dr. Anne Gunnarshaug Lien of SINTEF, Trondheim, and Dr. Ida Bryn of Erichsen & Horgen, Oslo.

Finally, I would like to thank my colleagues at SINTEF Architecture and Building Technology and Department of Building Technology, NTNU, for providing the perfect social environment for my work, for their care and cheerful support.

Last, but not least, I thank my husband, Jan Ove, for always being there, and my little daughter, Ingvild for bringing my thoughts away from the “serious” work and into a world of bright sunshine.

Summary

The background for this thesis is based on the assumption that the success of solar buildings relies on the assessment and integration of all the different design objectives, called *criteria*. These criteria are often quite complicated to deal with (e.g. environmental loading) and may be conflicting. The different design issues and the many different available energy technologies call for different areas of expertise to be involved in the design of solar buildings. This makes it difficult to evaluate the overall "goodness" of a proposed design solution. Also, the communication between design professionals and the client becomes complicated.

The goal of this work was therefore to produce a means for the design team and clients to be able to better understand and handle holistic solar design. A first hypothesis was that a structured approach for evaluating design alternatives might be a means to this end.

In order to specify an approach that would fit into the building design process, an analysis of design process theory and building design practice was carried out (chapter 2). Also, special solar design issues were investigated. This analysis resulted in the following conclusions:

- Most building design processes start out with no clearly defined goals or criteria of success. The design criteria are refined and discovered through evaluation and feedback on alternative design proposals.

- Design involves a lot of subjective value judgements, and decisions are often based on experience, "gut feeling", or intuition. Design options are evaluated based on quantitative and qualitative performance measures. There exists no objective optimal design solution.

- It is possible to identify some main activities that are common to most design processes. These are categorized into 4 main tasks: *problem formulation, generation of alternatives, performance prediction* and *evaluation*. The activities are very much overlapping and dependent on each other.

- Decision-making in design happens mainly through evaluation of proposed design solutions.

- Close cooperation between the design team and the client is imperative for the success of solar design. It is important that solar energy considerations are included in the early design stages because the decisions taken here are essential for achieving a well-integrated solar energy system.

This led to the conclusion that a structured approach for evaluation of alternative design options is useful and important, but it has to be seen in relation to the other design task, i.e. put into a framework.

The next task was therefore to search for useful ideas for structuring evaluation in the early design stage. The search was concentrated on the building industry and the field of decision analysis. The field of decision analysis was included because evaluation is an important task within this field.

The result of the search was that some structured approaches to evaluation were found within environmental planning and the emerging field of "green building" assessment. These methods resembled somewhat the Multi-Criteria Decision-Making (MCDM) methods that were found within the field of decision analysis.

The next task was then to evaluate these methods with respect to use in building and solar systems design. This evaluation was based on the findings in chapter 2 about the design process characteristics.

The first conclusion was that a structured side-by-side comparison of alternative solutions seemed to be essential to evaluation. However, a simple side-by-side comparison of alternatives with respect to the different criteria, will in most cases not be sufficient to reveal the best alternative. This is due to the fact that the goals are often conflicting or apparently incommensurate. Therefore, some sort of aggregation of the performance measures into an overall measure of "goodness", is useful. From the survey of multi-criteria evaluation approaches, the Simple Additive Weighting (SAW) approach appeared to be most suitable. Various applications of SAW approaches were found in the "green building" and environmental impact assessment tools. The SAW-based methods were also found to be the most simple and intuitive of the MCDM approaches. The main advantage of the SAW model is that it makes value judgements explicit, thereby acting to increase mutual understanding among the design team participants and the client about what is important to focus on. It is also important that both qualitative and quantitative values can be incorporated in the model. The model is also quite flexible, thus it can be tailored to individual needs. A problem of the method is that it is quite difficult to create commensurate measurement scales and elicit representative weights. Therefore, scaling and weighting techniques were investigated in more detail. It was concluded that it might be possible for the design participants to create scales and weights to be used in an evaluation based on a SAW approach that is adapted for the building design process. However, appropriate guidance is needed, especially concerning how to create commensurate measurement scales.

A structured evaluation approach based on the SAW method was then developed and put into a building design framework. The framework was separated into 4 parts, *problem formulation, generation of alternatives, performance prediction* and *evaluation.* Although the main emphasis is placed on the evaluation part, the other tasks are included since the different tasks are very much interconnected and overlapping. Three different approaches to creating measurement scales are proposed. The first approach is an open approach relying on the participants to create their own measurement scales, given certain guidelines, and including consistency checks. The second approach involves using linear measurement scales. The third approach involves defining a special type of logarithmic scales based on qualitative categorization.

The evaluation approaches were then exemplified and tested in 3 different building projects. The first case was a project that aimed at designing an a-Si PV facade concept for office buildings. The participants defined their own measurement scales. The second case project was a test of the evaluation approach in a meeting between researchers and practitioners working on the preliminary design of a school building. In this case, the participants used pre-defined linear measurement scales. The third case included an implementation of the multi-criteria evaluation approach in an ongoing design project, using the logarithmic type scales.

The test cases suggested that the multi-criteria decision-making framework helped organize the design work and facilitated carefully balanced and integrated evaluations. It provided a common reference for the design team to synthesize all judgements and values in the early design, and promoted documentation of the choices. However, further testing is needed in order to streamline the approach and to confirm whether the framework is an efficient means to promote holistic solar design.

Contents

1 Introduction

1.1 Background

There is a wide range of available solar technologies and design strategies that may quite easily reduce the energy consumption of buildings by more than 50% compared to conventional designs. In spite of this, it is a fact that solar and low energy measures in buildings have not gained widespread use. My hypothesis is that this is mainly due to the lack of three factors: *economics*, *knowledge* and *integrated design*:

Economics
The installations are capital intensive and the energy prices have been too low for a rapid return of investment. The common economic models tend to emphasize the investment cost and put little weight of the returns earned in the future. Very often, the added investment cost due to a solar strategy are viewed only as an isolated expense, and not put into the total economic framework. The cost of energy for operating buildings is not a significant part of the total running costs of an organization or company. Cleaning and O&M (operation and maintenance) costs, for instance, are typically significantly higher than the energy costs, (Bjørberg, Eide et al. 1993), (Morton and Jaggar 1995), (Flanagan, Norman et al. 1989). Compared to the cost of staff (wages, social, etc.), all the "technical" costs are quite insignificant. Thus, the focus on the high investment costs seems to be a serious obstacle to widespread use of solar and low energy systems.

Knowledge
There is generally too little knowledge about how solar and energy saving strategies work, and how to successfully integrate them into buildings.

Integrated (holistic) design
Building design involves the consideration of a wide range of complex issues, requiring expertise within fields ranging from structural engineering and environmental sciences, to architectural and psychosocial issues. An integrated approach to building design seeks to incorporate all the important aspects in a holistic synthesis. It views the individual systems not as isolated entities, but closely connected and interacting with the rest of the building. In an integrated approach, all the different design criteria need to be focused on simultaneously and traded off against each other in order to optimize the "overall goodness" of the design. Khemlani and Kalay describe the problems of integrated design as follows (Khemlani and Kalay 1997):

"Buildings must fulfill a host of diverse criteria, abide by innumerable codes and rules, and an ever-increasing list of constraints. A direct consequence of this increased complexity has been an enormous growth in the number of diverse

professionals who need to be involved in the design and construction of a building…..Specialization makes the already involved process of building design even more intricate and time-consuming. All the individual design and construction specialists do not work together on a design. Not only are they physically located in different places, they are also not usually working on the same design model….. Over and above the communication issue, however, there is yet another serious problem that specialization brings in its wake. It is very difficult, if not impossible, for the specialists to have a clear vision of the "overall goodness" of the project. Due to their limited time limits, each specialist tries to optimize the design for his/her own discipline, which quite conceivably may come at the expense of other disciplines."

Unfortunately, solar and energy saving measures have often been implemented and "optimized" without taking the whole building performance into account. The "optimization" procedures employed usually only include energy and economic performances, at the most. There are numerous examples of how comfort issues, environmental issues and aesthetics have not been properly valued in the design of energy efficient buildings. The strong focus on energy efficiency in the 1970's demonstrated that an emphasis on one performance area (energy) is likely to result in failure in other performance areas, such as air quality. In the 90's the pendulum has swung the other way; we now see a strong emphasis on indoor air quality. In Norway, this has brought forward requirements of large supplies of fresh air volumes, which naturally leads to an increase in the energy consumption. These are typical examples of the lack of holistic thinking. In general, people tend to overemphasize issues that can be modeled numerically. We spend a lot of time calculating the daylight factors in a room, but tend to forget that these figures really tell us very little about the sensation of the lighting quality in the room. There is no use spending a lot of time on detailed calculations of aspects that are either of marginal importance to the stakeholders[1], or have little effect on the overall value of a design.

In a recent article about low energy building design, Dr. J. Douglas Balcomb puts the issue of energy efficiency in perspective (Balcomb 1999):

"Among design strategies, daylighting – the use of natural light to replace artificial light – fills a unique niche. It stands alone as the most important design issue. Because daylighting affects the form and layout of the building, the decision to use it must be made early in the design process. Arguably, the most important reasons to daylight a building are, in decreasing order, to improve the aesthetics of the indoor environment; enhance the productivity of the occupants; decrease peak electric loads; reduce emissions of pollutants from power plants, including CO_2, SO_2 and NO_x; and save on energy and operating costs ……………. So, if the focus is only on saving energy, we miss the most critical factors."

A solar energy building should not be designed primarily to save energy, but to provide a comfortable and pleasing place for people to live or work in, while making a limited impact on our natural environment. Buildings have a long service life that involves many different participants or stakeholders: designers, builders, investors, users, maintenance personnel, etc. An integrated design approach includes a

[1] A stakeholder of a business is defined as any individual or group who has an interest in the business because he can effect, or is affected by the activities of the business. The stakeholders in building projects will be described in section 3.3.

consideration of the interaction between the building, it's different stakeholders, and the environment in a life cycle perspective. There is much disagreement among professionals, users and the general public about what constitutes a "good building". Especially when it comes to issues like aesthetics and "environmental friendliness", the disagreement and uncertainties are large. In our increasingly complex world of science and technology, there is a growing skepticism to the technical professions, as described by Hugh J. Miser:

Since the early 1960s, the professions have faced a growing crisis of confidence and legitimacy. Artifacts of science and technology have exhibited unhappy properties about which their designers have not forewarned the public: Large industrial and energy plants generate acid rain at great distances; nuclear energy plants seem not as safe as the public had thought them to be; safety in the technical workplace has become a public issue. Professionally designed solutions to public problems have had important unintended consequences, sometimes worse than the problems themselves. Widely publicized disagreements among professionals on possible approaches to public problems have undermined the confidence in the knowledge bases for many of the advocated approaches (Miser 1988).

During the design process, a lot of choices have to be made based on more or less "hard data", and many judgements and value trade-offs have to be carried out. If the professionals are really serious about making good buildings and keeping their credibility, they need to cooperate in such a way that the overall "goodness" of the design can be clearly understood. Only in this way can we achieve an integrated design approach.

To conclude, the main hypothesis of the thesis is that *good façade-integrated solar energy systems are a result of a holistic, multicriteria design process and will gain from some sort of formal, multi-criteria evaluation approach.*

1.2 Objectives

The objective of the work is to develop a method for multi-criteria decision-making in solar design that will be a means to achieve more integrated design. The main goals of the method should be:

- to help find what design issues that are important to focus on
- to help synthesize the design issues in order to evaluate the overall "goodness" of the design solutions
- to promote documentation of the choices

The design criteria should include both quantitative and qualitative issues, such as environmental loading, resource use, comfort, architectural quality and economics. The method should help the design team and the client (defined below) to find the most efficient way through the myriad of different solar design strategies while taking care of several different design objectives.

The early design phase of a building project is especially important. The main factors that determine the buildings' effectiveness with respect to utilization of solar energy are determined in the briefing and concept/scheme phases. For example, the orientation, zoning, and façade layout are more or less determined in the schematic design. Therefore, the main focus of the method will be on the early design phase. However, if possible, the method should also be useable in later design stages.

The method and guidelines developed in this work are primarily aimed towards the different participants of the design team and the client. The construction of the design team may differ from project to project, but essentially it consists of a design manager and experts from different design professions such as architects, HVAC and electrical engineers, construction engineers. The word "client" is used to mean the individual or organization that is paying for the design and construction project. The methodology should mainly be a means to help communication between the different members of the design team, and between the design team and the client. However, the method should also be directed towards the other stakeholders of the building project, e.g. future occupants, government agencies, or "neighbors", at least as a means of documenting decisions. Since the design team manager is responsible for the integration of the work of the design team, the overall responsibility for implementing the method in the design process would naturally belong to him.

It is my hope that through the use of this method for multicriteria solar design, better solar buildings will emerge. The approach should help the decision-makers to keep a balanced view of the design work and prevent them from being swept away by one single performance measure. Another valuable contribution that the thesis could make is that of increased knowledge transfer. I hope it would help each member of the design team (from the different design professions) to understand and value the work of the other members, so that they could create buildings that better satisfy the needs of the stakeholders.

I realize that in order to achieve fully integrated solar design there is still a long way to go. I do not believe that this thesis will solve the entire problem. However, I hope that it will challenge the established way of designing buildings and that it will be one of the steps that will help ease the way towards integrated solar design.

1.3 Limitations

The methodology will be illustrated for commercial buildings. These are selected because they are complex buildings (employ many different technologies and strategies), they consume a significant amount of energy, and they are very visible to a large number of people. However, the main part of the thesis will be of general use for building design.

Also, the methodology will only be illustrated for buildings in Norway. However, the main principles would most likely also be valid for other countries.

1.4 Content and Scientific Method

The work within this thesis has been organized as follows:

1. Investigation of how building design is carried out in general, and solar design in particular. This is based on literature studies of design theory, design process case stories, and design tools (chapter 2).

2. Evaluation of the results in order to identify what design process characteristics have implications for a multicriteria design method (chapter 2).

3. Further investigation and evaluation of the different design tasks in order to put them into the framework of multicriteria solar design (chapters 3, 4, and 5).

4. Survey of methods for multicriteria evaluation used within the building industry and the fields of decision analysis and environmental impact analysis. Evaluate methods and conclude which aspects are relevant with respect to use within this framework, based on the findings of points 1-4 (chapter 6).

5. Development of a method for multicriteria decision-making based on the findings of points 1-6 (chapter 7).

6. Testing of method in case studies of commercial building projects in Norway (chapters 8, 9, 10, and 11).

7. Conclusions and refinement of the method based on test results (chapter 12).

2 The Design Process

2.1 Introduction

In order to make a method for multicriteria solar design that fits into the design process, it is helpful to understand how building design is carried out, and solar design in particular. It may also be useful to take a wider look at design approaches in general. Hence, this chapter includes an overview of how building design is carried out and described. It also investigates some general design and decision-making approaches. Finally, it describes the special characteristics of solar design.

Section 2.2 gives a brief description of building process stages, i.e. how the design evolves and what tasks are carried out.

Section 2.3 deals with design theory. It includes a literature survey of how design has been described by different authors, i.e. how designers work.

Section 2.4 broadens the view by looking at problem solving and decision-making techniques in general. The substance of this chapter is acquired from other areas such as product design, operations research, economics, management and policy analysis. Two fields of study that were found to be of special interest for the work in this thesis were *systems analysis* and *systems engineering*.

In section 2.5, the special characteristics of the building industry are reviewed in order to identify important constraints for the development of a multicriteria design approach.

Section 2.6 gives an introduction to solar energy systems, briefly explaining the main strategies. Emphasis is placed on building integration issues.

In section 2.7, typical characteristics of solar design processes are described. This is mainly based on the results from an international research project where several case stories from actual building projects have been documented.

In section 2.8, common solar design tools are described. These include design handbooks, simple calculation methods, and computer simulation programs. The description is very brief, including short mentions of central design tools and their main contents. However, two new computer simulation tools are described in more detail because they include elements that are very interesting for the work in this thesis.

Section 2.9 summarizes the findings of chapter 2 and points out what might be worthwhile to focus on when developing a framework for multicriteria solar design.

2.2 Building Process Stages

The 6 phases of a design project:

1. Enthusiasm
2. Disillusionment
3. Panic
4. Search for the guilty
5. Punishment of the innocent
6. Praise of the non-participants

In the building industry, it is common to split the design process into separate stages. Usually, 3 main stages are identified: *brief*, *concept/scheme*, and *engineering (detailed design)*. Table 2-1 shows a typical description of the stages in the design and construction processes.

Table 2-1. Stages in the design and construction processes

Main work stages	Tasks
Brief (programming)	Statement of need Brief development
Concept & scheme design	Feasibility studies Concept (schematic) design Design development
Engineering (detailed design)	Detailed design Production information Bill of quantities
Procurement	Tender action Project planning
Construction	Operations on site
Completion	Commissioning and hand-over

The first step is to formulate the problem, the needs and requirements of the client, and to establish a set of criteria that will form the basis for assessing and establishing the need for the building. These may include functional specifications, timing requirements and priorities. This is followed by a description of the building's intended function.

The statement of need is translated into a plan with space requirements. A more precise definition of the functional and technical requirements is then developed. From this, a definition of the project and reliable estimates of cost and time can be produced. Donna P. Duerk (Duerk 1993) has presented a model of issue-based programming that shows the evolution of design concepts based on facts, issues and values, to create goals and performance requirements for the design:

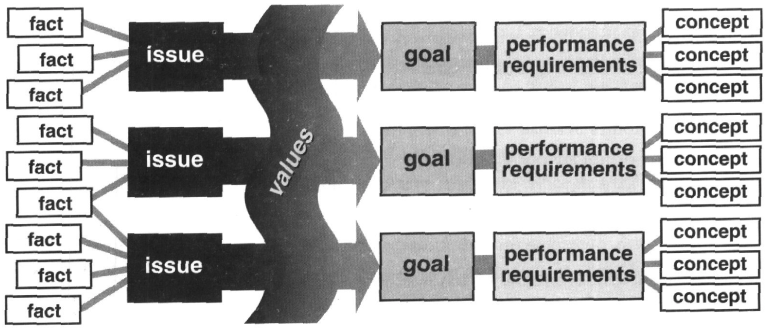


Figure 2-1. A model of schematic design programming, (Duerk 1993).

The concept and scheme phases include evaluation of different alternative designs. Factors that are evaluated may include:

- site layout
- plans, use of space, communications
- elevations, façade design
- principles for structure, acoustics, safety
- principles for mechanical and electrical services
- principles for material use, quality

A more detailed cost and time plan is also presented in this phase. The different stages in the design process may be more or less overlapping in time, i.e. part of the briefing/and programming may be going on after the design work has begun.

The listing of different stages indicates a linear model of the design process. This linearity can definitely be questioned. It is probable that the designer thinks more freely across and around the boundaries of a problem. A complex cyclic model is therefore more realistic and representative of the process, see Figure 2-2. There are two parts to this model:

- the iteration and evaluation within each part
- the iteration and evaluation between parts

At any point it may be necessary to move to another part and evaluate it to understand the original problem. The process is one of continually cycling between and within the part of the evaluation. In practice this tends to fall into three stages: preliminary evaluation, probable solution and final solution.

If this interactive and reflective approach to design is typical, then it makes a methodical and analytical approach difficult to adopt. This is because the process is difficult to specify in advance and the evaluation against many criteria is likely to lead the designer in unexpected directions.

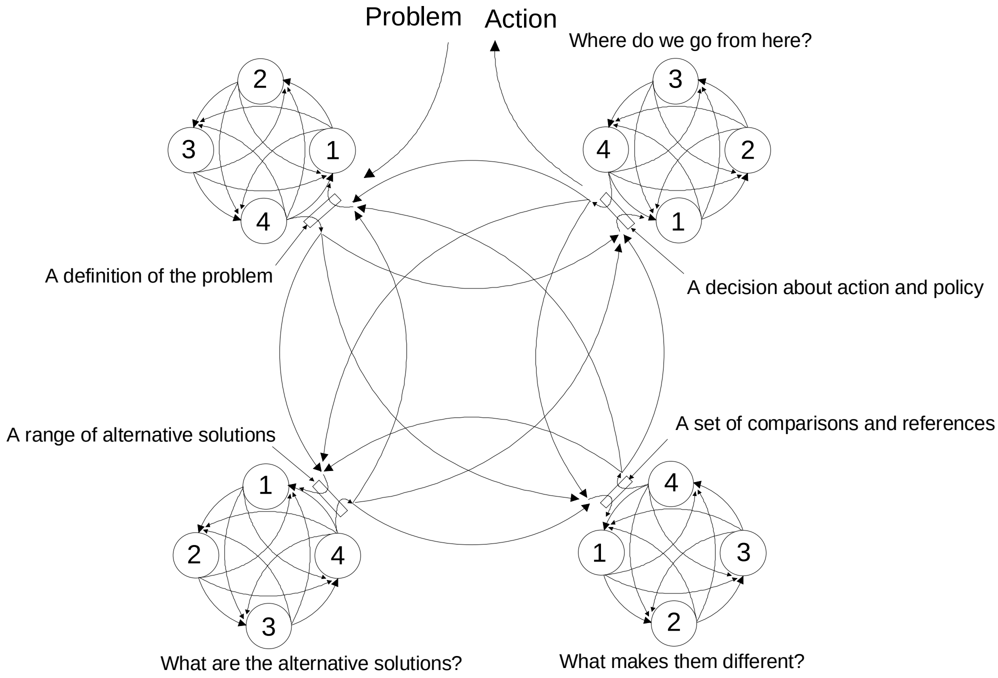


Figure 2-2. The "continuous whirling process" model of design, (Gray, Hughes et al. 1994).

The building process stages may also be illustrated in a total life cycle perspective, including not only the design and construction phases, but also use and operation, changes and retrofits, and demolition. Figure 2-3 shows a cyclic life cycle model indicating that the different phases may occur many times during the lifetime of a building. Since important benefits of solar design appear in a long time frame, the life cycle perspective is especially important.

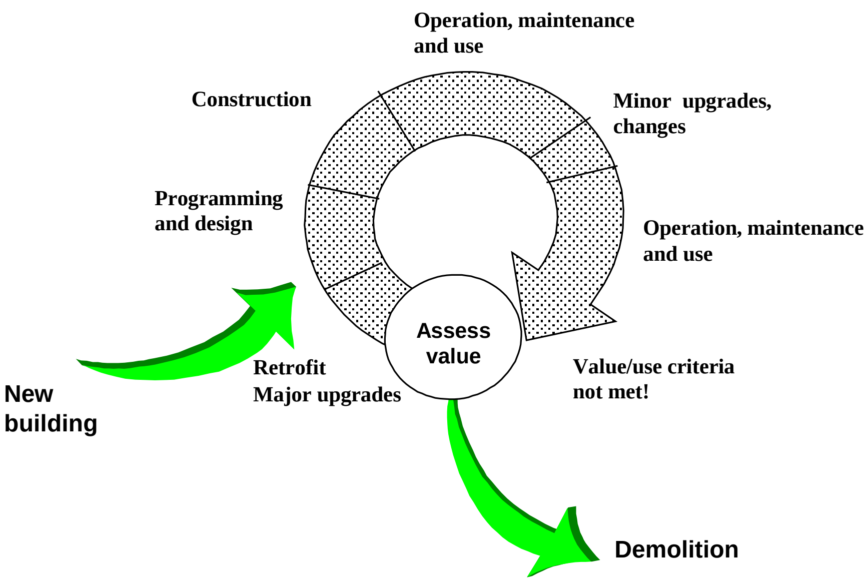


Figure 2-3. The life cycle of a building. (By courtesy of Siri Blakstad, 1997, Faculty of Architecture, Norwegian University of Science and Technology).

2.3 The Design Process

In order to prescribe a methodology that fits smoothly into the design process, it is useful to understand the methods and rules that design is governed by. Although many attempts to describe the design process have been made, there is no consensus or general theory about how design is handled.

The different views on design methodology have been classified into three generations, (Lundequist 1992; Lundequist 1998):

The first generation stems from the early 60's and is characterized by the view that design is a problem solving process, where the problems can be solved by dividing them into sub-problems. The design process itself is divided into three separate steps: analysis – synthesis – evaluation (hereafter called the "ase-model"). These steps are repeated throughout the design process:

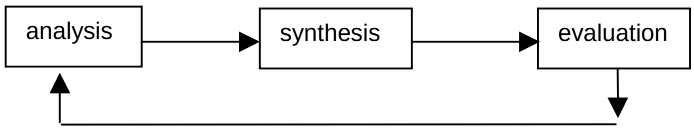


Figure 2-4. The "ase-model".

The analysis phase includes an unconditional gathering of information, reformulation of this information to criteria, and a division of these criteria into sub-criteria. The synthesis comprises the creation of sub-solutions, each being a solution to some of the sub-criteria. The evaluation is a test of how well the selected sub-systems and solutions match the different criteria. This last stage also includes a decision about whether to move on. The first generation design theory is characterized by a belief in a logical-mathematical and systematic, rational handling of design. Although this design theory has received substantial criticism, part of this theory is still a basis in modern education within architecture and construction.

The second generation design theorists criticized the first generation's belief that it is possible to gather and categorize information without any presumptions. However, the second generation did not completely reject the "ase-model". Rather, they argued that the "ase-model" gave a too simplified picture of the practical design work. The design work is characterized as a dialectic process, they claimed, where a design hypothesis is posed against a set of criteria for good solutions, and where both the hypothesis and the criteria are changed and amplified throughout the process.

The third generation design theory was initiated in the late 70's and is characterized by recognition of the tacit, contextual knowledge in design. Design thinking is considered an obvious part of human intellectual skills, equally important and fundamental as linguistics. "Design is a special way of thinking" became the slogan.

During the 80's design theory was developed, primarily through Schön's adaptation of Simon's ideas about modeling and simulation as the central activity in all design work (Simon 1969). Simon viewed design as the construction and use of models for developing a basis for the client's decision. He also argued that the designers first generate a set of alternatives and then test them against a set of criteria. In his renowned book: "Reflection in Action", Donald Schön presents design work as a dialectic between technical-rational thinking and intuition (Schön 1983). The designer is supposed to master both of these thought and knowledge forms. Schön describes design as a "handling of problem situations" rather than problem solving. He argues that designers are collecting information about different alternatives through simulation of their performance in a model of the situation. Problem handling involves handling of uniqueness, uncertainty, instability, and value conflicts. This also involves evaluation, learning from experience, and surpassing established routines to find new solutions to new problems (Schön 1983; Molander 1993).

The Swedish design professor Jerker Lundequist also views design as a handling of value conflicts (Lundequist 1998): *The result of a design process is a product whose properties are decided by the people that has been involved in the project. Design therefore involves value conflicts. A value statement may be argued for or against through the use of a rational system of criteria.*

The British architect and psychologist, Bryan Lawson, who has published a series of books about design methodology, has made numerous observations and descriptions of design processes. Among his main findings are (Lawson 1997):

- Design problems cannot be comprehensively stated. Both objectives and priorities are quite likely to change during the design process as the solution implications begin to emerge.
- Design problems tend to be organized hierarchically (e.g. doorknob – door – wall – room – building – town – country – society). There is no objective or logical way of determining the right level on which to tackle such problems. The decision depends on the power, time and resources available to the designer, but it does seem sensible to begin at as high a level as it is reasonable and practicable.
- There is an inexhaustible number of different solutions.
- There are no optimal solutions to design problems. Design almost invariably involves compromise.
- Design inevitably involves subjective value judgements.
- Designers must be able to balance both qualitative and quantitative criteria in their decision making process.

Recently, Papamichael and Prozen have presented a design theory as a basis for the development of a computer-based design tool with multiple criteria such as energy, comfort and environmental issues (Papamichael and Prozen 1993), (Papamichael, LaPorta et al. 1997). The computer program is presented in section 2.8. In their paper "The Limits of Intelligence in Design" (Papamichael and Prozen 1993), Papamichael and Prozen present a design theory along Schön's lines, where they suggest that design involves "feeling and thinking while acting", supporting the position that design is only partially rational. They claim that design decisions are not entirely the product of reasoning, rather, they are based on judgments that require the notion of "good" and "bad", which is attributed to feelings, rather than thoughts. Designers do not "know" the relative importance of design criteria, they feel it continuously throughout the design process, re-formulating it as they compromise between what is desired and what is possible. The authors claim that this design theory suggest very well defined limits to the role of intelligence in design, which become constraints on the potential use of computers. Furthermore, they claim that most of the current efforts in computer-based design tools violate these constraints through the use of multi-criteria evaluation techniques, conflict resolution methods and optimization algorithms. Such models are inappropriate for design, the authors claim, because they force designers to make premature judgements, by requiring an explicit, a-priori knowledge of the desired performance. Based on this new design theory, Papamichael and Prozen suggest that research and development efforts should concentrate on computer-based *simulation of performance*, *factual databases* and, most important, appropriate *user interfaces*. The new concept for the computer-based design tool (Papamichael, LaPorta et al. 1997) is based on the theory that building design is characterized by the following main stages:

- Generation of ideas and solutions (strategies and technologies)
- Performance prediction of potential solutions
- Evaluation of potential solutions

They stress the importance of viewing decision-making as evaluation, through the assignment of "goodness" or "appropriateness" to the predicted performance. Since "good" and "bad" only make sense when there are at least two of a kind, the computer tool offers performance evaluation through side-by-side comparison of alternatives. See section 2.8 for a further description of the computer program.

In order to better understand how building design is going on, also some descriptive research has been carried out. A research group at the Institute of Advanced Architectural Studies at York identified nine methods used by the architectural practices (small and large) they studied (Mackinder 1980):

1) subjective selection
2) selection based on the availability of test information
3) selection based on functional analysis
4) selection based on feedback
5) selection based on study of user requirements (user participation)
6) selection based on habit or experience
7) standard specification
8) performance specification
9) computer-aided design

The researchers found that the subjective selection was extremely common. This might include systematic listing of criteria, but depended on final choices made on the basis of an individual's or group's knowledge and experience. Previous use and experience were found to influence selection more than any other factor. There was a strong tendency in all offices to develop a vocabulary of favorite products.

Through a series of interviews with well-known British architects, Darke (Darke 1978) showed that the architects tended to latch onto a relatively simple idea very early in the design process. This idea, or the primary generator, as Darke calls it, is used to narrow down the range of possible solutions, and the designer is then able to rapidly construct and analyze a scheme. Also, she observed that the architects did not start with the brief and then designed based on this. Rather, they started to design and brief simultaneously; the two activities were completely interrelated. Rowe (Rowe 1987) presented further evidence supporting Darke's idea of the primary generator. When reporting his case studies of designers in action, he wrote: "several distinct liens of reasoning can be identified, often involving the a priori use of an organizing principle or model to direct the decision making process.

In the book "*The Successful Management of Design. A Handbook of Building Design Management*", Gray et al. present the following observation (Gray, Hughes et al. 1994):

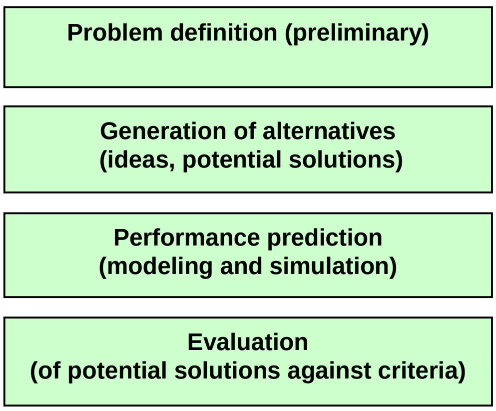
"The strategy that appears to be most consistently used is one that focuses on identifying several possible solutions or hypotheses. These are evaluated and each evaluation is used to refine the proposed solution until an acceptable answer is reached…. It seems essential to the design that the designer proposes one or more possible solutions to the problem at an early stage, even if this is only to obtain a clearer understanding of the client's needs. Essentially, design is a cumulative strategy of developing a solution and critically appraising it to see whether or not it meets the criteria of the client."

And further they conclude:

- *the search for the perfect solution is potentially endless*
- *there is no infallible process or solution*
- *the process involves finding as well as solving problems*
- *design inevitably involves subjective value judgements*
- *there is no simple scientific approach to solving the design problem*

Conclusions

To sum up, the descriptive and prescriptive studies cited above suggest the following central activities of building design:



The activities are overlapping and the process is cyclical or iterative, where both solutions and criteria are continuously explored and refined. The tasks of problem definition and generation of alternatives are dominated by creativity and tacit knowledge. In the two last tasks (performance prediction and evaluation), formal and analytical methods are more commonly used.

Design is a blend of technical-rational thinking and some sort of "intuition" or tacit knowledge. This knowledge is grounded in the knowledge and experience of the design team members. Building design also involves value conflicts and judgments. It is the implementation of the tacit knowledge, the values and judgements that is the most complicated part of the design work. However, this is also the most important part because it is decisive for the final outcome of the design work.

2.4 Problem Solving and Decision Making

In fact, many fields have similar approaches to problem solving and decision making. Within the fields of systems engineering, operations research, systems analysis, value engineering, decision analysis, and policy analysis, many similarities in the descriptions of problem solving approaches can be found. They all use some sort of problem structuring, identification of criteria and alternatives, evaluation and final choice, as illustrated in Figure 2-5. The process starts with structuring of the problem. The next phase is the process of model structuring. Here the focus is on identifying alternatives and criteria. It is described as a dynamic process, interacting with the process of evaluation, involving much iteration, search for new alternatives and criteria, discarding, reinstating and redefining old ones, and extensive discussion among the participants. Evaluation involves comparison of the different potential solutions in order to make a choice.

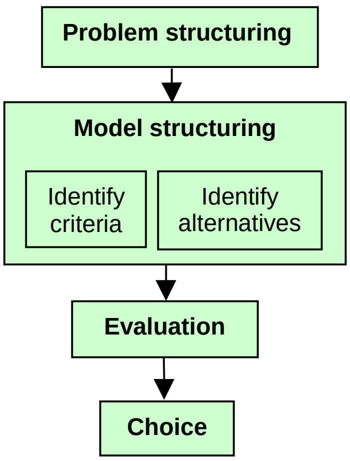


Figure 2-5. The process of problem solving, adapted from Belton (1990).

Ralph L. Keeney (Keeney 1992) identifies the most crucial activities of decision making to be: identifying the decision problem, creating alternatives, and articulate the objectives. Focusing on alternatives, Keeney argues, is a limited way to think through decision situations. It is values that are fundamentally important in any decision situation. Alternatives are relevant only because they are means to achieve one's values. Keeney notes that there should often be iteration between articulating values and creating alternatives, but the principle is "values first". He refers to this thinking *as value-focused thinking* (as opposed to *alternative-focused thinking*). Keeney argues that it can significantly improve decision making because values guide not only the creation of better alternatives, but also the identification of better decision situations.

On the other hand, it may be difficult to extract the stakeholders' values without presenting concrete alternatives. Kirk and Spreckelmeyer (Kirk and Spreckelmeyer 1993) argue that "*It is probably counter productive to think strictly in terms of clients' values without considering what those values mean in a very real and physical setting. A client will not necessarily be willing to share with the entire design team enough of his or her values to describe a problem accurately, especially in the case of problems that might be considered controversial, politically sensitive or unfamiliar.*"

Inevitably, decision making is a part of the design process. Decisions about whether to proceed with a particular design, decisions about what technologies to use, and so on, need to be taken. Bazerman (Bazerman 1998) argues that human judgement is an important part of all decision making:

Although a variety of decision aids (computers, decision trees, and such) are available, most important managerial decisions require a final decision or recommendation based on human judgement. Thus, human values and preferences are at the core of the decision-making processes in all organizations.

In his book "Judgment in Managerial Decision Making", Bazerman describes six "ideal" steps of decision making (Bazerman 1998):

1. *Defining the problem*. Many times managers act without an understanding of the problem to be solved. When this occurs, the manager may solve the wrong problem.
2. *Criteria identification.* Most decisions require the decision-maker to accomplish more than one objective. In buying a car, you may want to maximize fuel economy, minimize cost, maximize comfort, and so on. The rational decision-maker will accurately identify all relevant criteria in the decision process.
3. *Criteria weighting*. The criteria identified are of varying importance to a decision-maker. The rational decision-maker will know the value he/she puts on each of the criteria identified (e.g., the relative importance of fuel economy, cost, and comfort).
4. *Alternative generation.* The fourth step in the decision-making process requires identification of possible courses of action. An inappropriate amount of search time in seeking alternatives is the most common barrier to effective decision making. An optimal search continues until the cost of search outweighs the value-added information.
5. *Rating each alternative on each criterion.* How well will each of the alternative solutions perform on each of the defined criteria? This is often the most difficult part of the decision process, because it typically requires forecasting events.
6. *Computing the optimal decision*. Ideally, after the first five steps have been completed, computing the optimal decision would consist of multiplying the expected effectiveness times the weighting of each criterion times the rating of each criterion for each alternative solution; the solution with the highest expected value would be chosen.

Bazerman concludes that "*unfortunately, this represents a very simplistic view of the decision making process*". He goes on to describe how decision making is going on in practice:

In his Nobel prize work, Simon (Simon 1957) suggested that individual judgment is bounded in it's rationality and that we can better understand decision making by explaining actual, rather than normative ("what should be done") decision processes. The bounded rationality concept provides a framework for questioning the historical assumptions of the rational model of the individual, and it provides a foundation for the study of deviations from rational judgment.

Bazerman argues that the concept of bounded rationality suggests the following deficiencies in decision making (Bazerman 1998):

- Decision makers may lack information on
  a) the definition of the problem,
  b) alternatives,
  c) criteria, and
  d) the impact of choosing varying alternatives on the various criteria.
- Decision makers often have time and cost constraints that inhibit the search for full information
- Imperfections of the decision-maker's perceptions in obtaining information may effectively limit the quality of decisions.
- Human decision-makers can retain only a relatively small amount of information in their usable memory.
- Limitations of human intelligence constrain the ability of decision-makers to "calculate" the optimal choice accurately.

Within the fields of *systems engineering* and *systems analysis*, very structured approaches to product design have been developed. Therefore, it may be valuable to study the techniques of these fields in order to see if there are some aspects that may be useful in a building design framework. Short outlines of these approaches are given below.

Systems Analysis

Systems analysis is not a well defined methodology or distinct field. Miser and Quade (Miser and Quade 1988) put it this way: *We intend the term systems analysis to represent the portions of policy analysis, operations research, management science and other professional fields that share the structure outlined below, or some variant of it:*

Many of the problems of modern society emerge from interactions among people, the natural environment, and artifacts of man and his technology. Often such problems can be addressed by systems analysis, an approach that brings to bear the knowledge and methods of modern science and technology with appropriate consideration of social goals and equities, the larger contexts, and the inevitable uncertainties. The aim is to acquire deep understanding of the problems and use it to help bring about improvements. In practice, analysis of this type clarifies and defines objectives; searches out alternative courses of action that are both feasible and promising; gathers data relevant to – and projects the nature of – the environments for which the *actions are proposed; and generates information about the costs, benefits, and other consequences that might ensue from their adoption and implementation*

Miser and Quade (1988) stress the importance of craftmanship to the success of a system analysis:

We have some theory or principle to guide us, but we must also use information from the many disciplines involved, instinct, common sense, hunches and especially craftmanship gained from experience.

The principal activities in systems analysis are illustrated in Figure 2-6 below. The following description is based on (Findeisen and Quade 1985), unless otherwise noted.

The analysis starts by transforming the problem situation into a more clearly defined problem. It is not always easy to take seriously the activities involved in problem formulation. There is sometimes a feeling that, until models are being constructed or alternatives are being evaluated, the real work has not begun. But, in fact, which models to construct, which alternatives to compare, and whether the study outcome is to be a solution feasible under defined uncertainties, a formal optimization, or a presentation of alternative possibilities, are all decided in the problem formulation stage. Problem formulation implies the following elements (Checkland 1985):

- isolating the questions or issues involved
- clarifying the objectives and constraints
- identifying the people who will be affected by the decision
- discovering the major operative factors
- deciding on the initial approach

It is expected that the problem formulation, among other things, will provide:

- a preliminary statement of the objectives and ways to measure their achievement
- a specification of some promising courses of action, i.e., alternatives
- a definition of the constraints
- an anticipation of the types of consequences to be expected, how to measure them, and possible criteria for ranking them
- a plan for analysis

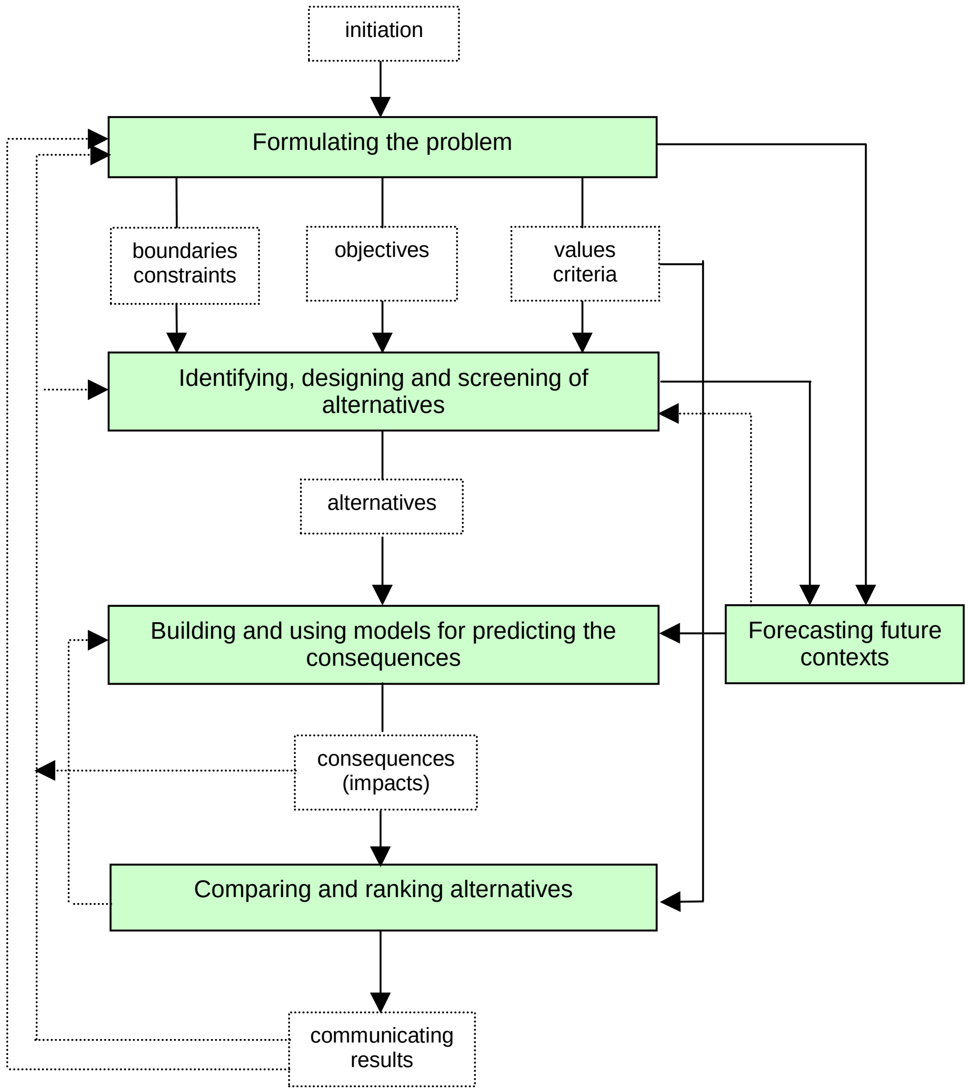


Figure 2-6. The systems analysis procedure with iteration loops (Findeisen and Quade 1985). (The figure does not show the essential continuing interactions between the analysis team and the decision-maker involved.)

The problem formulation stage can be seen as a small-scale systems analysis study in itself. It may involve a very broad range of inquiries into the hierarchies of objectives, the value systems, the various types of constraints, the alternatives available, the presumed consequences, how the people affected will react to the consequences, and so on. The models used for prediction, however, are still crude and may be entirely judgmental.

Generating alternatives is above all a craft or art, an exercise of imagination, creativity, criticism, and experience. The diversity of alternative ways of attaining an objective calls for creativity, ingenuity, and deep knowledge of the real-world situation, rather than for complete mastery of formal tools. Therefore, the guidelines given for generating alternatives can only be a loose framework which may help in some cases, but not in others.

Whenever a diversity of means exists to achieve the objectives, generating and selecting alternatives are best done in steps or stages. Initially it is appropriate to consider a fairly large number of possibilities as alternatives; any scheme that has a chance of being feasible and of meeting the objectives should be investigated. At the beginning, it is good to encourage invention and unconventionality; foolish ideas may not appear so foolish when looked at more closely. It may often be advisable to reach beyond the less rigid constraints, to broaden the scope of the study outside the limits that were initially set by the client.

The many alternatives that are considered initially cannot be investigated in detail. It would be too costly and, above all, excessively time-consuming. Some kind of screening, based on expert judgement, evidence from past cases, or simple models, can often be used to select a few of the alternatives as more promising. Grossly inferior alternatives and those that are dominated by others can be screened out. During the evaluation process the good features of the better alternatives may suggest ways for the analyst to design new and still better ones.

The stages that follow the initial scrutiny should include an increasing amount of quantitative assessment. At first, the assessment of the consequences of each alternative may still miss many details. Care should be taken that measures of effectiveness are treated only as approximations; that is, what is really better is not necessarily demonstrated by a simple arithmetic comparison. Forecasting of the future state of the world is required in order to predict the consequences of an alternative. Forecasting techniques range from scenario writing to mathematical forecasting models. Whatever technique is used, a forecast is always based on the past and current data, observations, or measurements, plus assumptions about connections of the future. When expert judgement alone is employed, it may to a large extent be carried out explicitly.

The last stage of the selection procedure should investigate relatively few alternatives, but in considerable detail. These alternatives should be serious candidates for implementation. At this stage, systems analysis sometimes overlaps with systems design or systems engineering, where the job is to determine all specifications for the consecutive design of the particular part of the system. Fine tuning is an activity that may, in appropriate cases, make good use of mathematical models. The problems are usually well defined and setting the details may be ideal for formal procedures for optimization, such as linear programming.

Systems Engineering

The following description is based on (Asbjørnsen 1992), (Fet 1997), and (Blanchard 1990).

The Systems Engineering process involves a series of steps accomplished in a logical manner and directed toward the development of a product or a production system. Systems Engineering is the effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top-down iterative process:

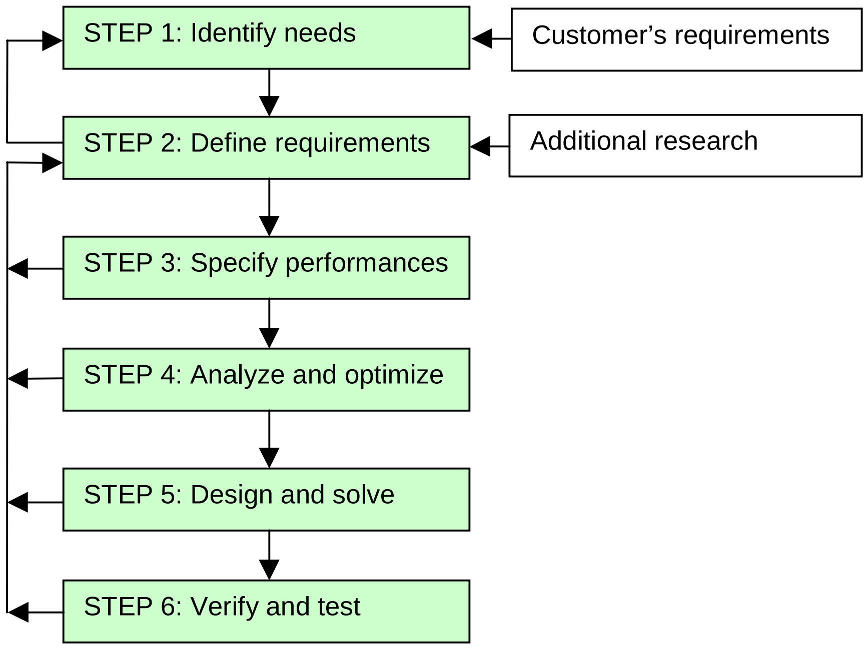


Figure 2-7. The Systems Engineering steps.

STEP 1: Identify needs
Based on the requirements of a client, a user group, or a market, a need is identified. This step includes an iterative loop where the statement of needs is an answer to the questions: "What is needed?, "Why is it needed?", and "How may the need be satisfied?" The statement of need should be presented in specific qualitative and quantitative terms, in sufficient detail to justify progression to the next step. Iterations are carried out until the need formulation is accepted.

STEP 2: Define requirements
Based on the needs, functional, operational and physical performance requirements to each system element are defined. Functional requirements have to do with the systems ability to carry out functions, or actions and reactions. The functional requirements are an answer to the "what's" in STEP 1.

Operational requirements are related to actions and functions to be carried out during operation of the system. An inherent requirement to the functional design of the system is that the system has degrees of freedom to make operational change possible. Therefore, the formulation of the operational requirements in systems engineering includes possible requirements from operators or computer control systems to be able to run or operate the system in a desirable fashion. The operational requirements may be an answer to the "why's" in STEP1.

Physical requirements reflect the needs for physical connections between subsystems and elements, describes the physical conditions the system will be exposed to, and how the system fits into the environment. The physical requirements may be an answer to the "how's" in STEP1.

STEP 3: Specify performances

The system requirements are then translated to performance specifications, i.e. definable and measurable performance criteria of the total system and its subsystems. The system is subdivided into convenient parts, and a functional analysis related to subsystems, system elements, and the integrated parts of the system, is performed.

The functional analysis is an iterative process of breaking requirements down from the system level to the subsystem, and as far down the hierarchical structure as necessary to identify input design criteria and constraints for the various components of the system. The performance specification helps ensuring that all facts of system design and development, production, operation, and demolition and support are covered. It also ensures that all elements of the system and its integrated parts (hardware, software, "humanware" and economy) are fully recognized and defined. Included in the performance specification should also be measures and conditions for measurements.

STEP 4: analyze and optimize

Based on the specified performances, a representative configuration should be selected. Inherent with the systems engineering process is an on-going analytical effort that involves evaluating various system design alternatives. This is called trade-off analysis, and may be defined as a compromise between conflicting interests with the need to maintain equilibrium.

The task is to select the best approach possible through the iterative process of system analysis using various models. The use of weight factors and information from interested parties is an important part of the analysis. Different optimization techniques are used. Fair and objective evaluation of systems requires a reproducible way of testing and evaluating. Therefore, the trade-off analysis should meet the following requirements:

- Define the objective function for the total system performance evaluation
- Define the conditions under which the system performance is to be measured
- Establish the measurement/evaluation criteria for a "best" satisfaction of the functional, operational and physical needs and requirements.

STEP 5: Design and Solve

The detailed design phase starts with the concept and configuration derived from the preliminary activities like system requirement specifications, performance specifications, synthesis and analysis. When the overall system definition has been established in an accepted conceptual design, it is necessary to progress through further definitions leading to the realization of hardware, software, "bioware" and economics. These should be evaluated in relation to their possible environmental impacts throughout the system's life cycle.

STEP 6: Verify and Test
In this step the system concept should be verified by simulation or by rapid prototyping compared with known reference systems. In particular the system performance should be tested according to the requirements set by the customers and users of the system.

In Systems Engineering, the necessity of a holistic view, the cash flow and quality view, and time effectiveness, is emphasized. A holistic view means that the different phases of the life cycle are interrelated, have an impact on each other, and they need to be addressed in the context of the whole. A long-range approach must be applied, and the life cycle considerations are essential.

The Systems Engineering process requires a teamwork where the professional skills of the team members are the platform for their participation in the process. The team members need to have a clear understanding of the needs and requirement of the user of the system and/or the customer.

Conclusions

Many of the models of problem solving and decision making resemble the models described within the design theory literature. The models resemble the "ase-model" described in section 2.3, including distinct phases of problem structuring (analysis), model structuring (synthesis) and evaluation. Many authors emphasize the importance of identifying the values of the stakeholders, but recognize that the values may not emerge wholly until later in the process when alternative solutions have been proposed. Also, it is widely recognized that human judgements is an important part of the decision process, and that this often results in a decision process that is far from rational. The descriptive research has identified a number of heuristic biases that makes the decision process deviate from the ideal. These "imperfections" include time limits, limitations of the human brain, and psychological factors.

Systems Analysis and Systems Engineering both include procedures and steps that resemble those of building design. They include some kind of problem formulation, the generation of alternative solutions, prediction of consequences for the solutions, and comparisons among them. Both processes emphasize the need for iterations between steps. The Systems Engineering process is more specific or "engineered" than the more loosely defined Systems Analysis. The latter seems to put more emphasizes on craft and judgmental procedures, which are also important in building design. They both stress the need to consider future issues and the life cycle perspective. In Systems Engineering, the holistic view is given special attention, i.e. including all design disciplines in the design team, evaluating the whole range of performance criteria including technical and human factors, and integrating the life cycle stages of the product. Therefore, there seem to be several aspects of these fields that may be useful in a building design framework.

2.5 The Nature of the Building Industry

The building industry of today has some special characteristics that may put constraints on the methodology for integrated solar building design. The increased complexity of buildings and technologies calls for many different specialists to be involved in the design process. Computer technology has enabled designers to manipulate large quantities of data quickly and inexpensively. Clients and the society as a whole are putting higher demands on documentation of complex issues, for example environmental concerns connected to the building industry.

The main characteristics of the building industry that affects the design, can be summarized as follows:

A high degree of specialization
Many different professions are involved in the design and construction of buildings. The increase in the number of people involved in the design process, the high degree of specialization, and the number of conflicting goals that requires satisfaction, has widened the communication gap between the users and designers of buildings.

Short time limits
There is a pressure to get the project finished in time due to competitive pressures, loans, fees, etc. In particular, the early design phase is very much pressured, it is not unusual that it receives less than 10% of the total budget for the design. This will restrict the amount of time for information search, which may again lead designers to focus on issues that are easily modeled and solutions that are well documented.

Separation of designers, owners, and users of buildings
Owners and users of the building are frequently not the same people. The building may be owned by one company, occupied by one (or more) other company, and run by a third company (outsourcing). The ownership, operation and occupation of a building may change several times during its lifetime. Therefore, the users of the building are often unknown to the designers, and their wishes and preferences are therefore hard to predict. Also, the wishes and values of the client are often very vaguely formulated..

Rapid development and information overload
There is an ever-increasing diversity of available products and technologies. Prices fluctuate much and change rapidly, and many new products and technologies appear on the market every day.

One-of-a-kind projects
Every building project is unique due to varying constraints such as client preferences, location, climate, etc.

Temporary design teams
Although designers may happen to have the same client and work the same building professionals, design teams are often not the same from project to project.

The importance of early decisions
The decisions taken in the early design phase are important because they may have a great influence on the quality of the end product. The further the design has progressed, the less opportunity there is to make a significant change, and the more expensive the change will be.

A wide range of performance criteria
Building design involves a wide range of performance criteria that are of both qualitative and quantitative nature. The criteria may be conflicting.

The importance of values and judgements
Many decisions taken in building design involve judgments. The different members of the design team perform judgements based on their knowledge, experience, and intuition. Often, these judgements are not well documented.

A far reaching perspective
Buildings have a long service life compared to other products, a life time of 30 years is quite common for normal building products like windows and facade elements. Some parts of the building may be changed with shorter intervals, e.g. the interior furnishings. However, viewed as a whole, buildings may have to serve for more than 100 years.

All buildings are solar collectors.

2.6 Solar Energy Systems and Design

Solar energy systems may be used to enhance the heating, cooling, ventilation, and daylighting performances of buildings. The main purpose of employing solar energy systems is to save energy and power (thermal or electric) while maintaining good indoor comfort conditions. Figure 2-8 shows typical figures for auxiliary energy consumption in an office building in Norway. The space heating load is primarily a result of losses by transmission and infiltration through the building envelope, and of losses through ventilation. These losses are partly offset by solar gains through glazing and by usable internal gains from occupants, lights, and appliances. The space cooling load is, on the other hand, a result of an excess of solar and internal gains. The introduction of stricter building codes, which generally address traditional energy conservation technologies that reduce the transmission and infiltration losses, have already resulted in a reduction in the energy consumption for space heating. As a consequence, the energy consumption for lights and appliances, as well as for space cooling and ventilation, is becoming more important. In fact, the electricity demand is in many cases becoming larger than the thermal energy demand. Thus, to reduce the total energy consumption of office buildings, designers of the future need to look at a wide range of solar technologies.

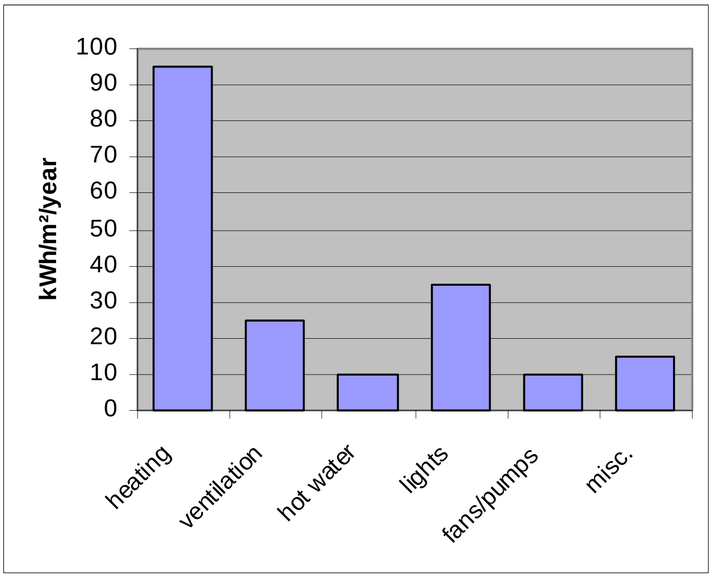


Figure 2-8. Typical energy consumption for an office building in Norway (NorEnergi 1993).

To make a good solar building, it is, of course, a prerequisite to know about the different system types, technologies and integration possibilities. Also, the designer needs to know how to assess the energy output of different systems in interaction with the building. In order to get an overview of the available options, it may be useful to structure the solar energy system types in groups according to their use and technical characteristics, as shown in Figure 2-9.

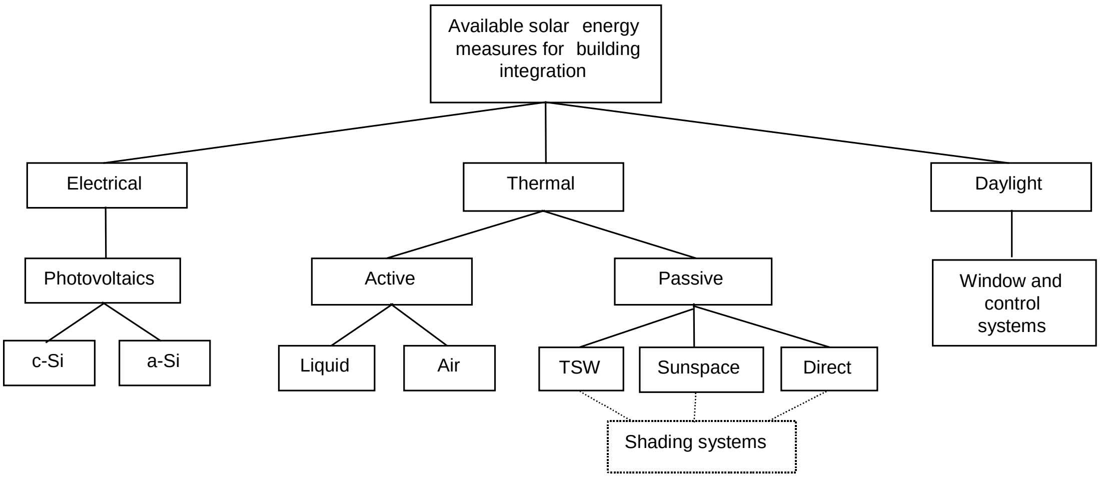


Figure 2-9. Solar energy technologies for building integration, structured hierarchically (TSW = Thermal Storage Wall, c-Si = crystalline Silicon photovoltaics, a-Si = amorphous Silicon photovoltaics).

The daylighting systems are closely connected to the passive solar energy systems, and may be treated as a part of these. Solar assisted ventilation may be treated as a part of the passive and active solar energy systems. This leaves 3 main types of solar energy system for building integration:

- passive solar energy systems for space heating, cooling and daylighting
- active solar energy systems for space heating and cooling, and DHW (domestic hot water)
- photovoltaics for electricity supply

The next three sections give brief introductions to the different types of solar energy systems. The main purpose is to give an overview of the key principles of solar systems. Emphasis is placed on building integration issues, such as collector size and appearance, distribution systems, comfort, etc. This should give a rough technological basis for understanding the main issues of building integrated solar energy systems. Since the presentation is short, references are given to useful literature in the field.

Passive Solar Energy and Daylighting

Passive solar energy systems are systems that primarily utilize building elements to collect, store, and distribute solar energy. They have traditionally been defined as systems that do not need auxiliary energy for operation. Most systems, however, function significantly better when a fan or a pump is used to assist circulation. Passive systems are therefore now usually defined as solar systems with a high degree of building integration. Passive solar design can improve building energy performance in heating, cooling and daylighting.

Passive solar heating systems are used to reduce the need for auxiliary space heating by collecting, accumulating and supplying solar energy using the common building components. There are basically 3 main types of passive solar heating strategies:

- *Direct gain systems*, where the solar energy enters directly into the room through "a solar window".
- *Indirect gain systems*, where the solar energy goes through a "solar wall" before it enters the room.
- *Isolated systems*, where the solar energy is collected in a "sunspace" that is separated from the living space.

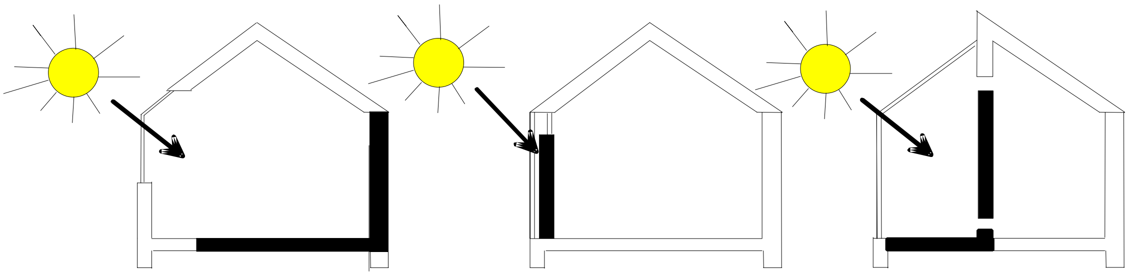


Figure 2-10. Three main types of passive solar heating systems (heat storing elements in black).

Utilization of the greenhouse effect is the key to passive solar heating. Glass and other transparent materials have the ability to let through short wave solar radiation. This energy is absorbed in floors, walls, roofs and furnishings and is afterwards released as long wave radiation. In this way the heat is trapped inside the building, because the long wave radiation is absorbed or reflected back from the glazing. Window design is therefore a central part of passive solar design. Key parameters are orientation, placement, solar energy and daylight transmission, thermal mass, and heat insulating properties. Also, the placement and solar absorption properties of heat storing constructions and the thermal zoning (room plan) of the building are of importance.

Passive cooling systems are used to save energy and improve comfort through the exclusion or removal of unwanted solar heat. When considering cooling, the rule is to first limit the amount of heat from solar radiation that reaches the building, then to minimize the amount of heat within the building envelope and to reduce internal gains form occupants, light, and appliances. Then, if it is still necessary, the final task is to remove any remaining unwanted heat.

Solar controls are used to prevent the solar radiation from reaching and entering the building. It is most effectively done by sizing, positioning, and shading of windows. Fixed or movable shading devices, such as overhangs, awnings, louvers and blinds, or the shading provided by appropriate vegetation, reduce unwanted gains through the windows.

Ventilation, using cooler fresh air driven through the building by naturally occurring differences in wind or air pressure (the stack effect), will also help reduce internal temperatures. The cooling effect of increased air speeds is also important. In relatively dry climates, the ventilation air can be cooled during the day by letting it pass over evaporating water using pools, fountains, or water sprays. Another way to cool the ventilation air is to pass it through pipes buried in the ground. In climates with large variations in temperature between day and night it is also appropriate to utilize the building mass for natural cooling.

Daylight design involves the provision of natural daylight to the interiors of buildings. This may produce energy savings as well as healthier and more pleasant living conditions. By adjusting the interior lighting according to the daylight availability, significant lighting energy and power savings may be obtained. Energy savings are obtained in two ways:

- Directly, due to the reduction in electrical energy for artificial lights.
- Indirectly, because the reduced lighting use will influence the total heat balance of the building.

In periods with excess heat, utilization of daylight will reduce the cooling demand because the period with the highest daylight availability coincides with the period with the maximum cooling demand.

Window design is, of course, central to daylight design. Orientation, placement, size, form and transmittance properties are essential variables. Also, the control strategy of electric lights, shading elements, and room layout has to be considered. In the recent years, special products and principles for enhancing the daylight usability have been developed. For example light channels, reflecting light shelves, glass prisms and lamellas may be used to direct the light deep into the room and give an even and good daylight distribution.

Further description of daylighting strategies are given in (Aschehoug and Arnesen 1998), (Baker, Fanchiotti et al. 1993), (Bell and Burt 1995), (Littlefair 1996), and (Løfberg 1987). Computer programs for simulating the distribution of daylight as well as the heating, cooling and electricity consumption of daylit buildings, are available (SUPERLITE, ADELINE, RADIANCE, DALITE). However, properly modeling of the daylighting in buildings is quite complicated, and consequently, the programs that are able to do this, are quite tedious to use.

More detailed descriptions of passive solar system design are given in (Aschehoug and Thyholt 1992), (Lechner 1991), (Lewis and Golding 1995), and (Yannas 1994).

Active Solar Energy

The characteristic of an active solar energy system, as opposed to a passive solar energy system, is that it requires an external energy input to operate. This energy is most commonly electrical energy to run pumps or fans. Active solar systems may be used for space heating and cooling, as well as domestic hot water heating.

Active solar energy systems consist of three main parts: the collector, the heat storage unit, and a distribution system. The solar radiation is absorbed by the collector, which has tubes, or channels that contain the heat transfer medium. The heat transfer medium carries the heat to the storage tank or directly to the load. The distribution system consists of pipes or ducts that carry the heat transfer medium, and pumps or fans to drive the heat transfer medium through the system. Most often, some kinds of system controls are also needed. The control system monitors the system performance and takes whatever action needed to ensure optimal energy output, i.e. turn on fans and pumps, close valves and dampers, etc.

The collector is the heart of the solar energy system; it is here that the actual transformation of solar radiation into thermal energy takes place. There are many different kinds of collectors, their design is dependent on what purpose they are used for. The flat plate collector is the most suitable for building integration. The basic parts of any flat plate collector are the absorber, the cover, insulation and enclosure. Not all collectors have a cover or an insulating casing. The absorber is essential because it is the element that performs the actual work of converting solar radiation into thermal energy and transferring it to the heat transfer medium. It is often a thin metal plate that is painted black or has a selective surface coating. The selective surfaces absorb most visible light (typically 98%), as black paint does, but they emit far less infrared radiation than painted surfaces. This results in lower heat loss from the collector, which, in turn, means higher efficiency.

A transparent cover may be used to increase the efficiency of the collector. This is especially useful if the collector is going to operate in cool and windy weather conditions. The cover plate acts as a heat trap, allowing solar radiation to pass through to the absorber, but blocking the transmission of re-radiated heat and preventing air currents from cooling the absorber. The cover is usually one or more layers of glass or plastics. Glass is often used because it is highly transparent to visible light and opaque to infrared wavelengths beyond 3 μm. Special surface treatments and designs are available that can reduce the convective losses including low-emissivity coatings and transparent insulation materials. However, there is a trade-off between reducing radiation passage into the collector and reducing the loss of collected heat.

Figure 2-11 shows a traditional liquid flat plate collector (to the left). The transparent cover consists of one sheet of tempered glass with EPDM weatherstrip seal. The glass is enclosed in an extruded aluminum frame. The absorber consists of an all-copper finned plate with a selective black coating. There is 1.5" insulation on the back and 1" on the side and the back is sheet aluminum.

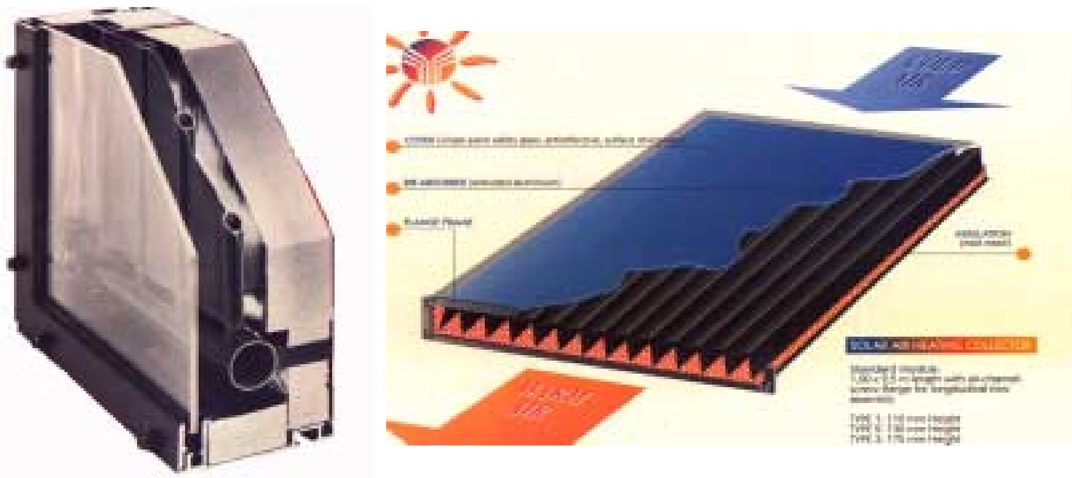


Figure 2-11. Left: Cross-section through a typical liquid-based collector (Solar Shelter). Right: A typical air collector (Grammer AG).

Air collectors are characterized by the effort to enlarge the conduction area between the absorber and the heat transport medium (air). Therefore, the absorbers of air collectors often are corrugated, perforated or equipped with fins and long air ducts to improve heat transfer. A typical air collector for space and domestic hot water heating is shown to the right in Figure 2-11. The rib absorber is made of extruded aluminum and the cover is a single-pane, tempered glass. The collector measures 1.0 by 2.5 m and is available in thicknesses of 110, 130 and 175 mm. The weight is 70-80 kg.

A well designed active solar heating system may produce a yearly yield of 500-800 kWh per m² of collector area. The systems are normally designed to meet only a fraction of the total load, typically less than 50%. Key parameters to consider when designing an active solar system is orientation of collectors, as well as the type and size of collector and storage. Detailed information about the design and application of active solar energy systems may be found in (Duffie and Beckman 1991) and (Rabl 1985). There are also numerous computer tools that may assist in designing an active solar system. However, most computer tools only consider energy and economic issues, and do not offer the possibility of interactive simulations of the active solar system and the rest of the building. This issue is further discussed in section 2.8.

Active solar heating poses challenges to architectural design of buildings. Space must be provided in the structure for energy storage units, piping and ducts, controls, auxiliaries, and associated equipment. Due to their rather "bulky" dimensions, and constraints on tube or duct length, it is not easy to integrate thermal collectors into the building envelope in an elegant and efficient way. As a part of the envelope of the building, the collectors will probably be a dominant architectural feature. The collector may serve as part of the weatherproof enclosure and thus allow a reduction in cost of roofing or siding; such a reduction is a credit that reduces the cost of the collector. Collectors may also be mounted like awnings, with improvements in performance but with increased cost of installation.

Photovoltaics

The photovoltaic (PV) effect is based on the transfer of the energy of light quanta to the electronic subsystem of a semiconductor and the collection of this energy within a short time - before it is converted into heat. The photovoltaic effect can be achieved by using many different semiconductor materials, the most commonly used is silicon.

The conventional silicon cell is constructed of very pure silicon doped with boron and phosphorous and sandwiched together to form a p-n junction, see Figure 2-12. When solar photons strike the silicon atoms, electrons are freed to flow from one layer to another, thus producing an electric potential (voltage). The resultant electrical current can then be harnessed through a metal grid that covers the cell and an external circuit to perform work. This effect continues as long as the cell is illuminated, and without the deterioration of any material or the consumption of additional energy.

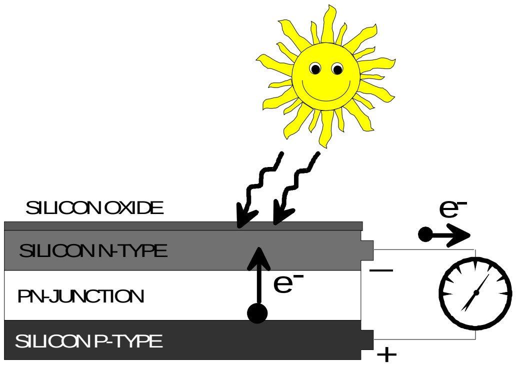


Figure 2-12. The silicon PV cell.

Three types of silicon materials are used for the fabrication of solar cells: mono-crystalline silicon (m-Si), poly-crystalline silicon (p-Si) and amorphous silicon (a-Si). Amorphous silicon solar cells differ in many respects from mono- and poly-crystalline silicon cells. Crystalline cells are breakable silicon wafers cut from large silicon blocks, while amorphous cells consist of a very thin layer of un-crystallized silicon which is deposited onto a carrier material (substrate). Therefore, amorphous silicon cells are often called thin-film cells. As a consequence, amorphous cells can have a variety of forms and dimensions, whereas crystalline cells have typical dimensions of 10 x 10 cm. Also, the different types of cells have quite different appearances. The mono-crystalline cells usually have an even, black or gray color, the poly-crystalline cells are most often bright blue and "shiny" because of the many small crystals, and amorphous cells are brownish or reddish-brown.

Solar cells are connected in a series and/or parallel configuration and placed in sealed units called modules. The module's top layer is purposely transparent and can be made from glass or plastics. The outermost cover keeps out water and gaseous pollutants which could cause corrosion of a cell and protects the cells from physical damage. The next layer is an anti-reflective coating designed to reduce the amount of reflected sunlight. The cell's bottom layer is called the back contact and is a sheet of metal which together with the front contact (the metal grid) is a bridge to the external circuit. To seal the whole structure, the back is covered with a layer of tedlar or glass. A frame of aluminum gives the module the needed mechanical stability.

The amount of power produced by a photovoltaic module is mainly dependent on the intensity of sunlight and the operating temperature of the cells. The output of the PV module is directly proportional to the amount of sunlight. The effect of temperature is not so obvious; PV devices produce less and less electricity as the operating temperature increases.

The efficiency for conversion of light into electricity depends on the cell material. The conversion efficiency of modules of amorphous silicon cells varies from 3 to 8%. Modules of poly-crystalline silicon have a conversion efficiency of about 9-12%, while modules of mono-crystalline silicon cells have an efficiency of 12-16%.

For buildings that are out of reach of the utility grid or for some other reason are independent of the grid, a storage or back-up system is required to ensure electricity production during cloudy periods or at night. Today, the only practical available storage options for PV systems are lead-acid or nickel/cadmium batteries. These two types of batteries are well known and available to the consumer. There are, however, limitations with respect to energy density, cycle life, temperature of operation and toxicity associated with both of these options. Alternative energy storage options are being developed that include other kinds of battery technology, fuels cells and hydrogen.

For PV applications in buildings, the inverter is a key component. The inverter is an electronic device that converts direct current to alternating current. In grid-connected applications PV electricity is fed into the utility network by means of an inverter. In stand-alone systems power inverters are needed to operate common appliances with electricity from the batteries charged directly by the solar generator.

The accurate sizing of a PV system is a quite complicated process, especially for stand-alone or hybrid systems. Most building integrated PV systems, however, are grid connected, since most buildings are located in areas within reach of the utilities. For these systems, simple design guidelines are available, see for example (Humm and Toggweiler 1993), (Peippo 1992), (Sick and Erge 1996), or (Strong 1991). For more accurate sizing of PV systems there are various computer tools that model the performance of different system types.

Due to their modular layout, lightweight and simple assembling, there are many possibilities for integration of photovoltaic panels into roof or facade elements. PV panels may replace or assist other necessary functions, such as weather skin or solar shading. In this way, it is possible to identify three main principles for PV integration into buildings:

1) Weather skin: roof and facade integration
2) Solar shading elements
3) Daylighting elements

The traditional PV modules are often not very suitable for integration into the building envelope. However, in the last few years, we have seen an increasing number of PV modules that are specially designed for building integration. These modules can fit into conventional roof and facade structures, such as for example glazing frames. Also, specially designed facade systems are available that ease the integration of PV modules into the building envelope. Some companies have specialized in supplying PV facade or roof systems, and offer PV panels as well as special structural components that go together with their modules. PV panels can be mounted as fixed shading elements over the windows, on awnings or venetian blinds. Using movable or semi-transparent PV elements, the combined function of shading and daylighting can be achieved. As shading elements, the PV modules are oriented towards the sun for maximum energy output, while blocking the direct radiation from entering into the building. Semi-transparent PV elements block most or all of the direct radiation, while allowing diffuse light to enter the room.

Building facades represent a dominant architectural feature, and are often designed to express the company's profile. Facade integrated PV modules can add exciting and elegant features to the building envelope. Figure 2-13 shows PV integrated into window and cladding systems.

Figure 2-13. Left: Crystalline silicon PV cells between glass panes in a German building (Pilkington Solar AG). Right: PV modules as a patchwork on a building in Switzerland (Solution AG).

2.7 Solar Building Design

How does the solar design considerations fit into the design process? In most projects, there is very little concern about solar and low energy measures in this early design stage. Advanced energy systems are often “added on” in later phases. Unfortunately, this is not a very efficient way of solar design, because the success of the solar design is very much dependent on decisions that are made in the schematic design phase (building form, orientation, facade layout, etc.). Also, the addition of a solar system may have significant impact on major design issues like comfort, aesthetics, etc. Even if the design process is iterative, there is a limit to how may iterations one may afford due to time and cost constraints. Figure 2-14 shows that the possibilities of making changes decrease dramatically as the design evolves, and that the costs of change increase similarly after the construction has begun. Thus, the decisions taken early in the design phase are crucial for the success of the project.

If energy efficiency and the use of renewable energy through solar design are design goals, this should be incorporated in the list of design criteria that are articulated in the pre-design stage. The definition of design goals and criteria is discussed in chapter 3. In this way, potential solar designs should be evaluated with respect to all design criteria in the early design phase. To do this, it is necessary to have energy expertise available already at this stage. The team can then evaluate the solar designs with respect to energy efficiency as well as other important design goals.

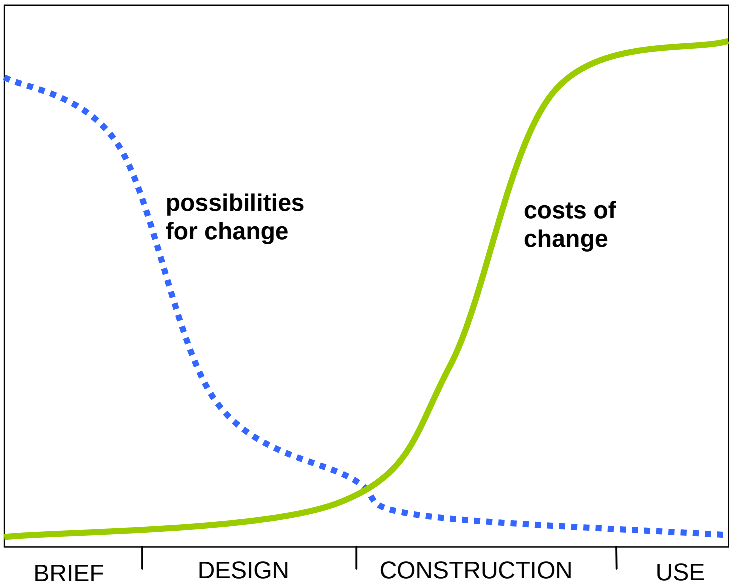


Figure 2-14. The possibilities and costs of influencing the functions of the building during the different life cycle stages. Adopted from (Bejrum 1991).

The Canadian project C-2000 (Larsson and Pope 1999), describes an integrated design process along these lines. The aim of the project is to help designers achieve high-performance buildings with low energy consumption and resource use, minimal environmental loading, good indoor quality, and improved functionality. The C-2000 Integrated Design Process comprise:

- Including a wide range of technical skills in the design team, containing an energy simulation specialist, and a design facilitator.
- Commencing teamwork from the very start of the concept design stage.
- Defining performance goals at the outset and referring to them throughout.
- Preliminary energy analysis in concept design phase.
- Preliminary performance assessment of a broad range design criteria in concept design phase.

Table 2-2 shows solar/low energy issues that need to be considered in the concept design phase. The table is mainly based on preliminary results of the work within the *IEA Task 23*[2] project (Jaboyedoff, Schuler et al. 1999), with some additions and adjustments based on (Wood 1998). The frame around the issues of building siting, layout, energy and costs is meant to designate that there are important interactions between these issues, which need to be taken into account. (GRIP 1998) gives a detailed listing of issues to be considered in the concept design and design development phases in ecological design of buildings. This list also includes examples of ecological design goals and examples of means to achieve the goals.

The first three tasks, i.e. *design team selection*, *site analysis* and *building program analysis* begin in the pre-design phase. The two first tasks will not be dealt with in

[2] This is a project within the International Energy Agency, Solar Heating and Cooling Programme, which was initiated in 1997 and ends in 2002. The name of the project is “Optimization of solar energy use in large buildings”.

this thesis. The third task – how to formulate preferences and criteria, is partly an issue of this thesis, and will be dealt with mainly in chapter 3. The next four tasks; *building siting*, *layout*, *energy concept* and *cost estimation*, all deal with performance prediction of potential design solutions. They do not however, represent a complete list of all design issues, but they include some of the considerations that are central to solar design. The details of how to do performance predictions of solar designs, is not an issue in this thesis. However, a discussion of how to find what design criteria to include and at what level of detail they should be treated, is included. This may be found in chapter 5 (Performance Prediction). The last two tasks; *concept design solutions* and *evaluation of concept designs*, are elements of the most central issue of this thesis; how to compare and evaluate potential solar design solutions with respect to a range of different criteria. Chapter 6 (Evaluation) treats this issue in detail.

Table 2-2. Solar design issues in the concept design phase.

Task	**Issues**	**Tools**
Design team selection	persons, qualifications, relations, experience, communication	qualification test
Site analysis	shading, surroundings, regulations, air quality, noise, wind	questionnaire
Building program analysis	preferences/criteria, use, time, density, loads	checklist
Building siting, mass disposition	orientation, regulations, placement	graphical design checklist
Building layout/shape	area/volume, zoning, light and air access	table
Energy/power concept	building shell, ventilation, daylighting, heating, cooling, internal lighting, comfort temperatures	rules of thumb simple methods or computer tools
Cost estimation	rough cost groups, differences, life cycle perspective	data base
Concept design solutions	List solutions, describe variations, advantages, disadvantages, consequences	matrix
Evaluation of concept designs	Comparisons, test against criteria, select solutions	

Within the *IEA Task 23* project, several solar design case stories have been documented (Henriksen 1999). The work includes descriptions of 21 actual building projects from different countries where solar and low energy features have been considered and implemented. Some of the main lessons learned from these case stories were:

- The energy/environmental goals of the projects were generally very vaguely defined. Typical examples of goal formulations are "*low energy consumption*", "*ecological building*", and "*low operating costs*". The reasons for the design goals (<u>why</u> a goal is viewed to be important), were generally not documented.

- The main obstacles for use of solar strategies were identified as: cost, time, lack of knowledge, appearance, and minimization of risk.

- The main motivations for use of solar strategies were identified as: to save energy, to achieve good comfort, to reduce environmental loading, and to reduce operating costs.

- Close cooperation between the members of the design team and the client is necessary to achieve good results. This was reported in almost all case stories.

- Simple calculation tools and rules of thumb were typically used to predict performance in early design phases. Advanced computer simulation programs were typically used in later design stages.

Thus, the solar design process has many common characteristics with the conventional design process described in section 2.3. The goals are usually not very clearly defined, and the design criteria include a range of different quantitative and qualitative issues. The integration of the knowledge of different specialists is imperative for the success of the project. The use of advanced computer simulation tools for performance prediction seems to be more prominent in solar building projects than in conventional projects. The next section deals with solar design tools in more detail.

2.8 Solar Design Tools

Solar energy systems are very much integral parts of the building. Thus, to work efficiently, solar energy systems must be designed with this in mind. This means that the interdependencies between the solar systems and the rest of the building; i.e. the structure, the envelope, the mechanical systems and the interior layout, must be carefully considered. Also, the choice of strategy should be based on a consideration of all design objectives, and not on energy-efficiency alone. The designers need to select the right technologies and combine and integrate them in the most efficient way. Trade-off considerations between competing solar strategies and conflicting design objectives must be carried out. This is the design approach which is the focus of this thesis; the *whole-building design approach*.

This chapter describes the state of the art of solar design tools, and points out their main pros and cons. The existing tools and guidelines to solar building design may be organized into three main groups:

- Design handbooks or manuals
- Simple calculation methods
- Computer simulation programs

Below, an overview of the most central design approaches is given. Since none of the design handbooks or simple calculation methods cover what is inherent in the whole-building design approach, only brief descriptions of these are presented. However, when it comes to computer tools, there are especially two new programs under development that contain some of the elements of the whole-building design approach. These will therefore be described in more detail.

Design handbooks give advice about what issues to consider along with descriptions of the different technologies and strategies. The majority of available books are devoted to technical descriptions of different energy related aspects of buildings. Most are specialized to one main type of technology, for example there are separate books about passive solar design, active solar design, photovoltaics, and daylight. For example, *Heating, Cooling, Lighting. Design Methods for Architects* (Lechner 1991), is an excellent and comprehensive design handbook that gives a thorough background on the technical issues of passive solar design. It is meant for the architectural designer to use in the schematic design phase. *Solar Engineering of Thermal Processes* (Duffie and Beckman 1991) is a comprehensive textbook on active and passive solar energy systems, mainly from an engineering point of view. The emphasis is on active systems, and building integration issues are not treated comprehensively. The last edition also includes a brief section on photovoltaic systems. *Photovoltaics in Buildings - A Design Handbook for Architects and Engineers* (Sick and Erge 1996) includes both engineering and architectural issues concerning the integration of PV in buildings. It also has a brief section on trade-off considerations between competing solar strategies and conflicting design objectives.

All of the available solar energy design handbooks are mainly concerned with the energy aspect. A few touch upon the issues of comfort, economics and architectural quality. The issue of environmental loading is barely mentioned in a few of the books. However, there are books on “green” or sustainable building design where solar design is treated as one of the sub-issues. The recent book *A Green Vitrivius* (Cofaigh, Fitzgerald et al. 1999), includes small sections on different solar energy strategies.

A few books give advice about how to structure the design work. For example, *Solar Energy and Housing Design* (Yannas 1994), describes the technical basis for passive solar design measures, and how these may be treated in the different phases of the design process.

No one single book pays special attention to integrated design of the whole range of solar energy strategies with regard to the whole range of design criteria. *The Building Systems Integration Handbook* (Rush 1986) contains detailed descriptions and systematic handling of the integration of different building systems with respect to six building performance mandates: spatial performance, thermal performance, air quality, acoustical performance, visual performance, and building integrity. However, innovative energy systems or solar strategies are not included (except for anecdotal references), nor is there any reference of environmental loadings.

Simple calculation methods are given in handbooks and in national or international standards like prEN832 (prEN-832 1999), or the coming prEN-ISO-13790 (prEN-ISO-13790 1999). They provide quick estimates of the energy performance of solar systems based on simplified physical relations, rules of thumb, or experience. As such, they may be very useful in an early design stage, to give a rough idea of the potential energy benefits of different solar design strategies. However, they don’t take into account all the interdependencies between different energy systems and the layout of the building, and should be used with caution. The LT Method (Baker and

Steemers 1995) is a simple calculation method that produces estimates of heating, cooling and daylighting performances based on a set of performances curves. The curves are drawn from a mathematical model where most parameters are given assumed values. Only a few key design parameters related to building form and facade design, glazing ratio, surface to volume ratio, etc., are left for the user to manipulate. This method gives a picture of the relative importance of the various energy components, but says nothing about the impacts on economics, comfort or other issues.

Computer simulation programs. A number of different energy simulation tools have been available to the building design community since the mid 70s. The majority of these programs were originally developed in mainframe versions by and for the research communities. However, many of the programs are now available in workstation and personal computer versions. Such programs include among others TRNSYS (Klein, Beckman et al. 1997), (Schuler, Meyer et al. 1996), DOE-2 (Birdshall, Buhl et al. 1990), BLAST (Andersson, Bauman et al. 1997), SUNCODE/SERI-RES (Berleman 1997), (Judkoff 1997), ESP (Clarke, Evans et al. 1997), TSBI3 (Johnsen, Grau et al. 1991), (Christensen and Johnsen 1996). The programs contain powerful algorithms to model the thermal behavior of buildings under varying environmental conditions. As such, they have the potential to give valuable input during the building design process for predicting the consequences of different design alternatives with respect to comfort, energy and costs.

However, the traditional programs are so complicated and time consuming that they are only used late in the design phase, if used at all. Thus, their influence on the final design is limited, since most decisions that have major effect on the energy consumption are settled in the early design phase. Also, the programs require input data at a level of detail that is not available in the early design stage. The output data are often presented in such a way that they are difficult to interpret for inexperienced users. In addition, most of the tools only give answers to specific questions. For example, some programs only calculate the energy consumption, others focus on the daylighting distribution, etc.

A new generation of computer based energy design tools is currently being introduced. These tools focus on the user interface and offer the opportunity to get quick and simple estimates of energy performance in the early design phase. A new aspect of these tools are also that they try to view the energy performance in a holistic perspective, that is, they are including other performance criteria such as daylighting, comfort (room air temperature profiles), economic (LCC) and environmental considerations (emissions of SO_2, CO_2 and NO_X from fuel burning). Two interesting tools of this generation, are *Energy-10* (Balcomb, Carrol et al. 1998) and *Building Design Advisor* (Papamichael, LaPorta et al. 1997).

Energy-10 (Version 1.2), developed by the National Renewable Energy Laboratory is a PC-based building energy simulation program for smaller commercial and institutional buildings. It is specifically designed to evaluate energy-efficient features in the early design stage. Energy-10 integrates daylighting, passive solar heating and low-energy cooling with energy-efficient envelope design and mechanical equipment.

Energy-10 is designed to allow for smooth and easy integration of energy efficiency in the early design. However, the program should also be useful in the later design phase. The figure below shows the intended use of Energy-10 during the design process.

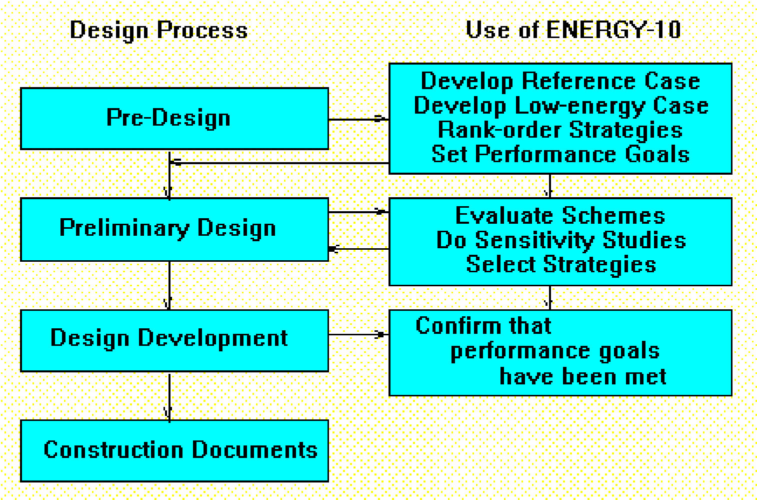


Figure 2-15. The use of Energy-10 in the design process (Balcomb and Beeler 1998).

Energy-10 requires only 5 inputs to start the simulation and analysis process: geographic location, total floor space, intended building use, number of stories, and type of HVAC system. From these basic inputs, Energy-10 automatically creates two simple "shoebox" buildings: one is a reference building constructed using standard construction practices; the other is a low-energy building that incorporates a number of energy-efficient strategies. The program runs a full year energy simulation and produces graphical output of heating cooling and lighting performances. The user can select graphical output in 27 different formats, all of which compare reference building to the low-energy building.

The current version of Energy-10 offers the possibility to apply 10 specific energy-efficient strategies:

Insulation, Thermal mass (of partitions), Passive solar heating (window area and orientation), Glazing (type), Shading (fixed overhangs and sidefins), Energy-efficient lights, Daylighting (on/off and dimming control, window size and placement), Economizer cycle, High-efficiency HVAC, HVAC Controls (heating setback, cooling setup, occupancy control).

The energy-efficient strategies are simply applied by checking off the desired measures in a special input window. The program can also do a rank ordering of the energy-efficient strategies according to their effectiveness. The strategies can be ranked by different criteria, such as energy savings, cost savings, or life cycle costs. An example is given in the figure below.

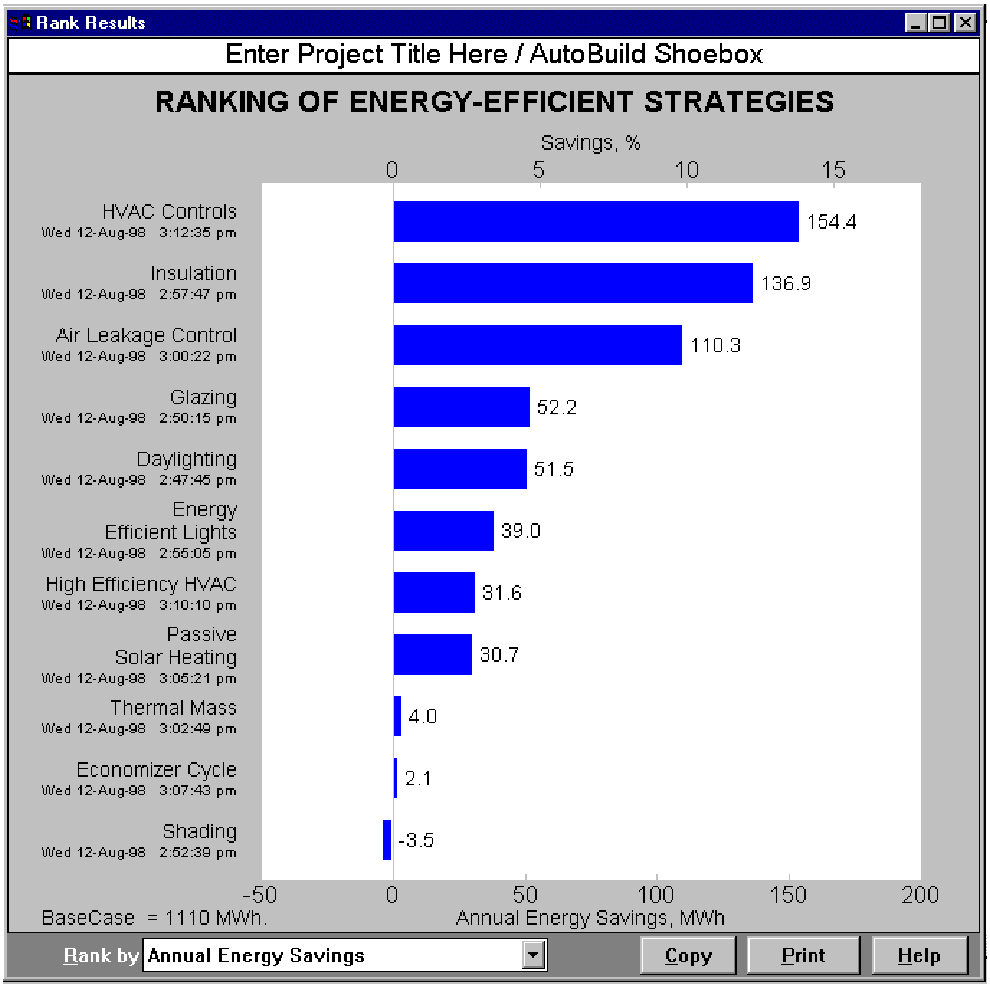


Figure 2-16. Graphical presentation of the results of a ranking of 11 strategies with respect to energy savings.

The *Building Design Advisor (BDA)* is developed by the Lawrence Berkeley Laboratory. This PC-based program acts as a data manager and process controller, allowing building designers to benefit from the capabilities of multiple analysis and visualization tools throughout the design process. The main objectives of the graphical user interface in BDA are to allow building designers to (Papamichael, LaPorta et al. 1997):

- compare *many* alternative building designs with respect to *many* performance parameters,
- review and edit values of input parameters in a consistent and orderly fashion, and
- select input and output parameters for review and comparison through enhanced display options.

These tasks are carried out by three separate graphical user interface elements; the *Schematic Graphic Editor*, the *Building Browser*, and the *Decision Desktop*.

The *Schematic Graphic Editor* is a stand-alone, CAD-like application that allows the user to draw and modify the geometry of a building. As the user creates building objects, the BDA selects "smart" default values from a Prototypes Database to prepare a complete input for the simulation tools that are linked to BDA. When, for example, the user draws a space in the Schematic Graphic Editor, BDA automatically creates wall, ceiling and floor objects along with default values for all required parameters.

The Building Browser (Figure 2-17) allows the users to navigate through the building representation and view objects and parameters, along with their values. The building objects are displayed in a hierarchical manner, similar to the standard Windows Explorer. In this way, the user may choose to see as much or as little information as he desires at the current design stage.

The Decision Desktop (Figure 2-18) allows for decision-making among alternative design options offering simultaneous side-by-side comparison with respect to the various performance criteria. The current version of BDA offers integrated performance evaluation with respect to heating and cooling, daylighting, and comfort (room air temperature profiles).

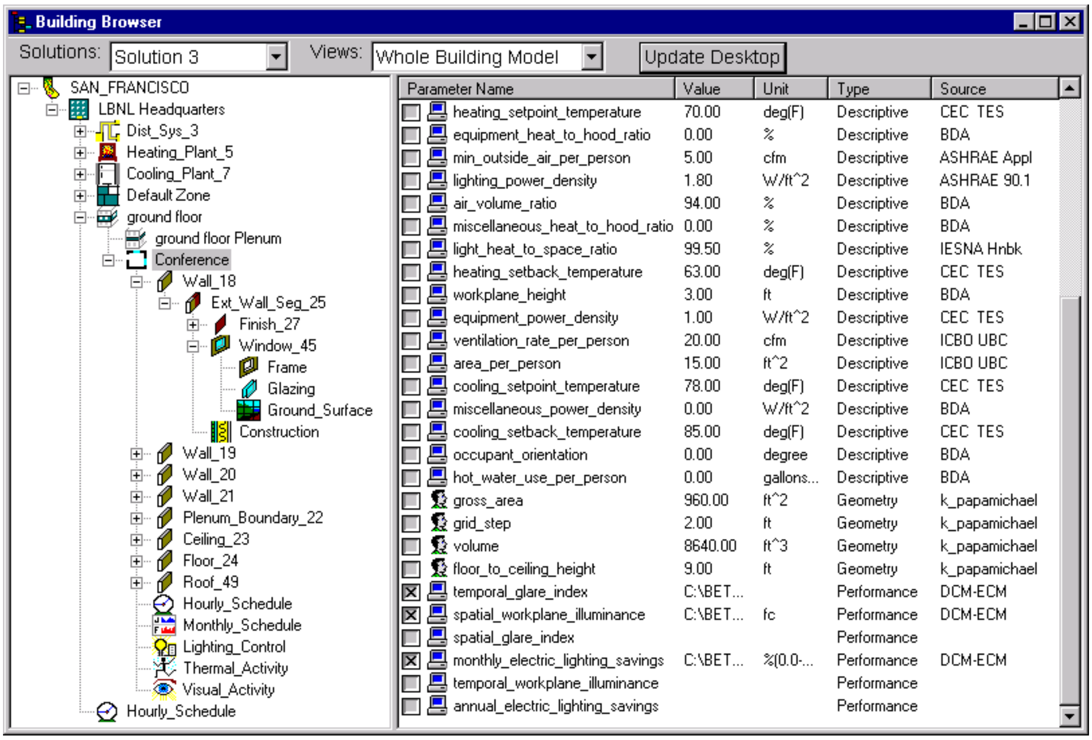


Figure 2-17. The Building Browser.

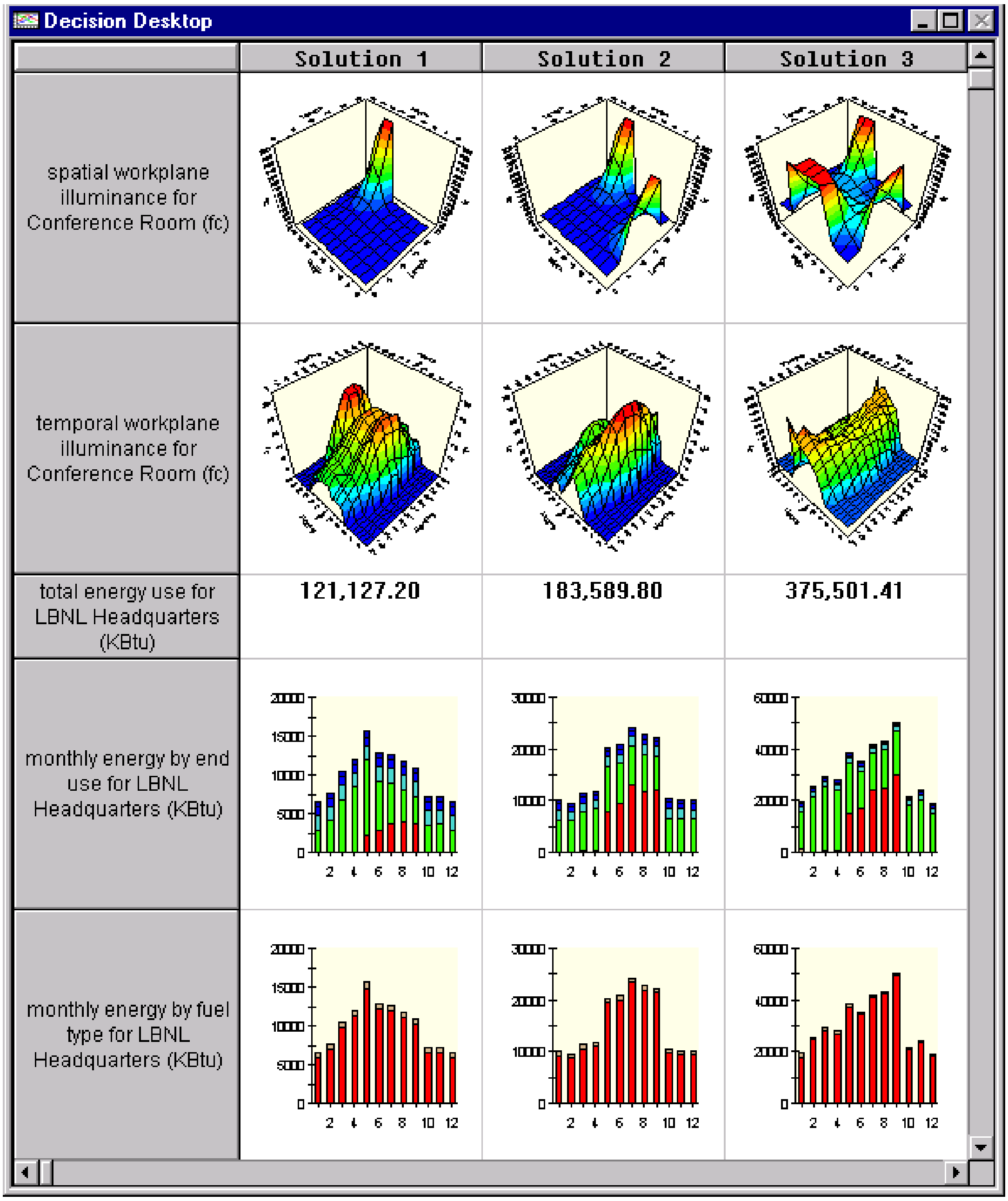


Figure 2-18. The Decision Desktop.

Conclusions

Available tools and handbooks make it possible to estimate (roughly or detailed) the energy performance of any isolated solar system or strategy. But the possibility for estimating the combined effect of different systems with respect to different design criteria, has been rather limited. However, new computer tools are emerging that offer the possibility to quickly evaluate many different design solutions against a range of different criteria. Although none of the tools currently include all of the major criteria or solar system types, they seem promising with respect to becoming useful tools for the whole-building design approach:

- They are quick and simple to use, yet offering advanced simulation possibilities. This means that the designers may get useful feedback on potential design solutions early in the design stage.

- They offer the possibility of viewing the performance of multiple design options against a set of different performance criteria (i.e. energy, power, daylight, thermal comfort, and emission of pollutants).

- They offer a certain amount of guidance to the user through listing of energy efficient measures and examples of standard buildings or "best practice" performance.

However, the computer tools only simulate the "hard" values, i.e. the ones that can be quantified numerically. In a building design project, there will always be the need for judgements of some kind. Evaluation of the total goodness of a design also includes soft values such as aesthetics. Conflicting performance goals also call for the need to perform trade-off analyses. This does not mean that advanced computer simulations are useless in building design. Still, it may be useful to listen to the words of R.E. Straunch (Straunch 1974):

"This is not to denigrate the value of quantitative methodology. It has great potential value, but as an aid to careful and considered human judgement, and not as a replacement for such judgment. When we forget that, and focus our attention too strongly on our methods and our computations as the source of our answers, we do not only fail to realize that potential, but we run the risk of being seriously misled. The source of knowledge and understanding about squishy problems has always been, and will continue to be, wise people more than sophisticated methods.

….. And if we fail to make it, there is no way we can realize the real potential of the people or of the methodology we do have available to us. I am not suggesting that we give up quantitative methods, but rather that we use them with a goodly grain of salt, and that we grant "the computer" no more automatic and unquestioned authority than we would grant a shaman or a fortune teller."

Bryan Lawson (Lawson 1997) uses the case of window design to give an excellent example of interactive, multi-dimensional design:

As well as letting in daylight and sunlight, and allowing for natural ventilation, the window is also usually required to provide a view while retaining privacy. As an interruption in the external wall, the window poses problems of structural stability, heat loss and noise transmission…… Modern building science techniques have generally only provided methods of predicting how well a design solution will work. They are simply tools of evaluation and give no help at all with synthesis. Daylight protractors, heat loss or solar gain calculations do not tell the architect how to design the window but simply to assess the performance of an already designed window.

Because design problems are so multi-dimensional they are also highly interactive. Enlarging our window may well let in more light and give a better view but this will also result in more heat loss and may create greater problems of privacy. It is the *very interconnectedness of all these factors which is the essence of design problems, rather than the isolated factors themselves.*

Thus, the role of today's computer tools is mainly to do performance predictions with respect to some criteria. There is currently no computer tool that can do the entire job of the building designer, i.e. generate "the optimal solution" on its own. Energy-10 does an attempt of guiding the user by providing a list of energy efficient measures to choose from, and through the use of the RANK function. However, there is no guarantee that this will produce the best possible solution, because there will always be other possible measures that are not included in the list. Also, there will be other criteria to be taken into account. The developers of the BDA program have accepted this "limit to intelligence in design", and do not attempt to give any kind of "intelligent" guidance. They restrict the computer assistance to simulation of performance and factual databases. The only guidance that is offered, is through an internet link to a web page of built examples.

The building designer may use computer tools to do a lot of runs to see the performance of different design options. At last he may end up with something that he is satisfied with. But how can he be sure he has found the best solution? There is no way that he can try out all possible types of systems and combinations. Also, since the programs only do performance predictions against some of the design criteria, the output from the programs does not represent the total goodness of the design. To do this, the combined knowledge of all the design professionals is needed. What is lacking is a methodology that can help the designers to integrate their efforts in order to search efficiently towards the best possible solution for their project. Computer simulation programs such as the above, may be useful tools for offering hard data to put into this methodology. However, they can not produce the entire answer to the design problem.

2.9 Conclusions

In an attempt to understand the underlying methods used in the creation of a design, a great deal of analysis has been undertaken of the nature of the intellectual process used by designers. Both prescriptive (normative) and descriptive approaches have been devised. What is clear is that there is no single method or system used by all designers, nor does any one designer appear to use any single method.

The Swedish design researcher Jerker Lundequist describes design as a process that starts out with diffuse goals, and therefore the designer has difficulties in using a specific method. The methodology that is applied during design is consequently based on heuristic searching rules, that is experience based rules-of-thumb for information search and problem solving grounded in available information (Lundequist 1998).

It seems like people tend to have individual methods for working that are tailored to their specific way of seeing the world. Consequently, one should be careful not to specify a too rigid and universal design methodology. A methodology that works for one person may be useless to another. In his book "Making it Happen – Reflections on Leadership", John Harvey Jones puts it this way:

”I find myself intolerant of management books that seek to prescribe exactly how it should be done. My own experience shows that there are many different ways of achieving one’s aims and many different ways of leading an industrial company… Each one of us has to develop our own style, and our own approach, using such skills and personal qualities as we have inherited. What each of us does over a long period of trial and error is to acquire a set of tools with which we are comfortable and which we can apply in different ways to the myriad problems which we need to solve.”

This represents a very individualistic view. It more or less neglects the fact that it would be more effective to learn from the experience of others instead of just go on a trial and error trip of our own. Even though a building designer may have his own style, it is probable that his search for good solutions will be more effective if he employs a structured approach. Also, since good buildings are the products of the combined efforts of the design team, the members of the design team must have some understanding of each other’s methods in order to communicate effectively. This is not to say that all designers need to have exactly the same approach. Obviously, one needs to account for the fact that people are different, and that the people in the design team are different from project to project.

Based on the previous chapters, the following points towards a structured approach:

- Designers face a lot of information. There are many different issues to include, and the amount of time that can be spent on each issue is limited and needs to be balanced against the design objectives. The information is easier to handle if it is structured.

- The high degree of specialization in building design may hamper the common understanding of the problem. Close cooperation between the design professionals in the early design phase is imperative for the success of solar buildings. A structured approach may improve information exchange and understanding among the different professionals and the client (or other stakeholders).

- Building design is a craft that involves judgments and value conflicts. A structured approach that aims towards making the value judgements more explicit would help the transfer of knowledge, and produce a common understanding about the problems. This would also facilitate the involvement of a wider range of decision-makers including users of the building, and offer documentation to the wider community. This is particularly important if one wishes to document environmental issues of the building.

The preceding chapters give the following requirements for the multicriteria design approach:

It should be a relatively open framework.
In order to fit into different design processes and suit different designers, it should not be a rigid methodology, but rather a basic structure that allows the individuals to fit it to their needs. Therefore, we may not call it a method at all, but rather a *framework* that can be used to guide the design team through the process.

It should be usable for the early design phase.
The decisions taken in the early design phase are crucial for the success of the project. It is therefore most useful to have a framework that can make this process as effective as possible. However, it would also be useful if the framework could be used in later design stages.

It should be simple, easy, quick to understand and use.
Because of the very limited time and resources of the early design phase, the method has to be quick and simple to use. This is a fundamental requirement of the framework; without this in place, the “method” would not be used at all. It also has to be so simple that a range of different professionals can understand it.

It should help understanding and promote communication.
Maybe the most important goal of the approach is that it should help the design team to better understand the problem at hand. By encouraging discussion and communication among the participants, misunderstandings, biases and “knowledge holes” may be uncovered, and a deeper understanding of the “holistic” problem may be gained. The framework should promote and simplify communication among the design professionals, as well as between the design professionals and the client (and other stakeholders).

It should handle values and judgements.
To increase a common understanding of the design, the approach should reveal values and judgements and make them as explicit as possible. It should also be able to handle value conflicts (trade-offs). The framework should support documentation of the judgements.

It should be an aid to organize and select relevant information and to focus on the most important issues.
The framework should help the design team to navigate through the huge amount of technical and non-technical information in an effective way. This means to help them find what issues are most important and relevant for the problem at hand. In this way, the design team would avoid jumping from issue to issue without progress or to get involved in heated debates over quite irrelevant issues.

It should comprise the entire life cycle of the building.
Buildings have a long service life and the major part of the resources is used after the initial design has been carried out. The design therefore has to try to incorporate future needs.

It should handle uncertainty and fuzziness.
Since future needs are hard to predict, the design approach needs to incorporate uncertainty. Also, some design issues can not be formulated exactly, like for example aesthetics. Therefore, the approach needs to incorporate vaguely formulated values (qualitative values) as well as quantitative values and uncertainties.

In the previous chapters, several main activities of design were described. Although there are many different approaches used, some activities seem to appear in all design processes. Since the different tasks are very much interrelated and overlapping in time, it may be difficult to describe them individually. Nevertheless, four main activities may be singled out:

- problem formulation
- generation of alternatives
- performance prediction
- evaluation of alternatives

The main focus of this thesis is to promote integrated, holistic solar design where all design criteria are included in a way that meets the values of the decision-makers. The most emphasis will be put on the evaluation activity. This is not because this necessarily is the most important task in the design process, but because it is a task where there is much to gain from a formal guide. The problem formulation task and the generation of alternatives rely more on experience, gut feeling and creativity. With regards to the task of performance prediction, a number of tools already exist that may help the designers a long way (see section 2.8). Nevertheless, there is still much work to be done within the field of performance prediction of solar systems, but this is not the scope of this thesis. The principles of performance prediction, i.e. the level of detail and measurement techniques, however, are treated in the thesis. It is clear that the evaluation task cannot stand alone. To be able to evaluate, some performance criteria and some alternatives must have been generated. The tasks are very much interrelated and overlapping. Also, the process should be iterative. The evaluation task should lead to refinement of the criteria and the alternatives. Therefore, the other tasks are also briefly described, and their relevance to the evaluation task is described. Chapters 3 to 6 are dedicated to a description of each of the four design tasks separately.

We fail more often because we solve the wrong problem than because we get the wrong solution to the right problem.

- R.L. Ackoff

3 Problem Formulation

3.1 Introduction

The first task of building design that was identified in chapter 2, is that of formulating the problem. One cannot evaluate a design solution without having formulated the objectives. Hence, problem formulation deals with identifying, structuring, analyzing, and understanding information and objectives. In building projects, the problem formulation is often considered to be in the programming/briefing phase. However, as was shown in chapter 2, the task of problem formulation is an ongoing activity throughout the design process. The values or objectives of the stakeholders[3] in a building project are the foundation for evaluating potential solutions.

In section 3.2 the concept of "value-focused thinking" is introduced. This concept suggests that the ideal building process should start with focusing on the values before going on to generate and evaluate solutions. Arguments are also presented to show that it is helpful to sort the design issues into a set of categories, called criteria. The criteria then serve to organize the design information and provide a basis for evaluate design solutions. Strategies for identifying relevant criteria are given. One means to help uncover objectives is to consider the needs and wishes of the building stakeholders through the life cycle of the building. This is described in section 3.3. Methods and tools for organizing criteria are then described in section 3.4. This section also illustrates what types of criteria that are commonly used in building design. The different methods for structuring criteria are evaluated and it is concluded that a hierarchical structure seems to be most suitable as a basis for a structured evaluation. In section 3.5 then, hierarchical structuring of criteria is described in more detail.

3.2 Value focused thinking

In his renowned book "Value Focused Thinking – A Path to Creative Decisionmaking", Ralph L. Keeney (Keeney 1992) describes an approach which he views to be the ideal foundation for problem formulation and evaluation of alternatives. This approach gives emphasis to the importance of specifying one's values before starting to generate alternative solutions:

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[3] A stakeholder of a business is any individual or group who has an interest in the business because he can effect, or is affected by the activities of the business. The stakeholders in building projects will be described in section 3.3.

Values are what we care about. As such, values should be the driving force for our decision-making. They should be the basis for the time and effort we spend thinking about decisions. But this is not the way it is. It is not even close to the way it is. Instead, decision-making usually focuses on the choice among alternatives available. It seems like as if the alternatives present themselves and the decision problem begins when at least two alternatives have appeared.

Keeney's theory of value focused thinking is comprehensively described in his book, and can't possibly be cited in detail here. However, the main principles of the model are considered to be important in this context. This is because the theory lays the ground for identifying and structuring objectives in order to be able to judge the consequences of several alternatives, assessing their relative desirability and performing sensitivity analysis of the results. The explicit value judgements are made possible through the value model, which forms the basis for evaluating the alternatives. Therefore, the main principles and background for Keeney's theory are described in the following.

The essence of value focused thinking is that values should be identified *before* the alternatives. This is opposed to *alternative focused thinking* where values are identified *after* the alternatives. Keeney argues that thinking about values is thinking about what you wish to achieve in a constraint-free way. Therefore it broadens the solution space and promotes creativity. Keeney describes several advantages of using value-focused thinking, they include:

- *Uncovering hidden objectives*. Thinking about values naturally provides an initial list of conscious values. This thinking may also provide keys to identify previously subconscious values.
- *Guiding information collection*. Values indicate what information is important. Specifying the values first will therefore prevent you from time-consuming efforts to collect information that turns out to be useless.
- *Improving communication*. The language of value-focused thinking is the common language about the achievement of objectives in any particular decision context. It is not the language of many specialties. This basis in common language should facilitate communication and understanding.
- *Facilitating involvement in multiple-stakeholder decisions*. Value-focused thinking makes the values explicit. This makes it possible to separate disagreements about possible consequences from disagreements about the relative desirability of those consequences. Otherwise, if the values are not explicitly considered, disagreements must be addressed in a general discussion about alternatives. Value-focused thinking may therefore help identify the basis for conflicts.
- *Evaluating alternatives*. Value judgements can be used to evaluate the relative desirability of alternatives. If the objectives are incomplete or not clearly defined, the insights based on evaluation with that value model are not sound.
- *Creating alternatives*. Value-focused thinking enhance the creation of desirable alternatives.

Keeney's value focused thinking can be described as a four-part concept:

1. Definition of the *decision context*.

2. Identification of the *fundamental objectives* representing the values of the decision-maker[4].
3. Identification of the mechanisms by which the objectives can be achieved, i.e. the *means objectives.*
4. Identification of the alternatives which have control over the mechanisms.

The broadest decision context for any decision-maker is the *strategic decision context*. It is defined by the set of all possible alternatives available to that decision-maker. The *fundamental objectives* corresponding to the strategic decision context are the decision-maker's ultimate end objectives; the *strategic objectives*. For a company, the strategic decision context may be "management of the firm". The *fundamental objective* in this context may be "to maximize the profits". Rarely are decisions addressed on the strategic level. The focus is almost always on more limited decision situations. It is therefore necessary to reduce the decision frame to foster useful thinking and analyses. This is done in two ways: the decision context is reduced so that fewer alternatives are appropriate, and, the fundamental objective for the decision context is reduced to limit the set of consequences of concern.

A fundamental objective characterizes an essential reason for interest in the decision situation. A *means objective* is of interest in the decision context because of its implications for the degree to which another (more fundamental) objective can be achieved. A means objective for a company with the fundamental objective "maximize the profits" may for example be "to decrease the sick leaves". Keeney argues that means objectives are useful for developing models to analyze decision problems and for creating alternatives. However, it is the fundamental objectives that are essential to guide all the effort in decision situations and in the evaluation of alternatives. In order to be useful for guiding all decisions, the objectives should be precisely, completely and unambiguously formulated. Keeney states that one of the most common mistakes is to formulate objectives that are too general to be useful.

To illustrate the relationship between different decision contexts and objectives, Keeny presents the decision frame of value focused thinking shown in Figure 3-2. This decision-frame is contrasted to the frame of alternative focused thinking, shown in Figure 3-1. In this figure, the framework is drawn with broken lines to make the point about what is missing; the fundamental objectives and the decision context which are not usually made explicit with alternative focused thinking. Points A, B, and C represent the alternatives in the set of all decisions. These alternatives are evaluated using a means objective or a set of means objectives. There is not necessarily a match between these objective and the available alternatives. Pictorially, there are several points representing alternatives near alternatives A, B, and C in Figure 3-2 which are not identified and yet could contribute to the same means objective.

[4] A decision-maker is defined to be an individual or organization or any other decision-making entity.

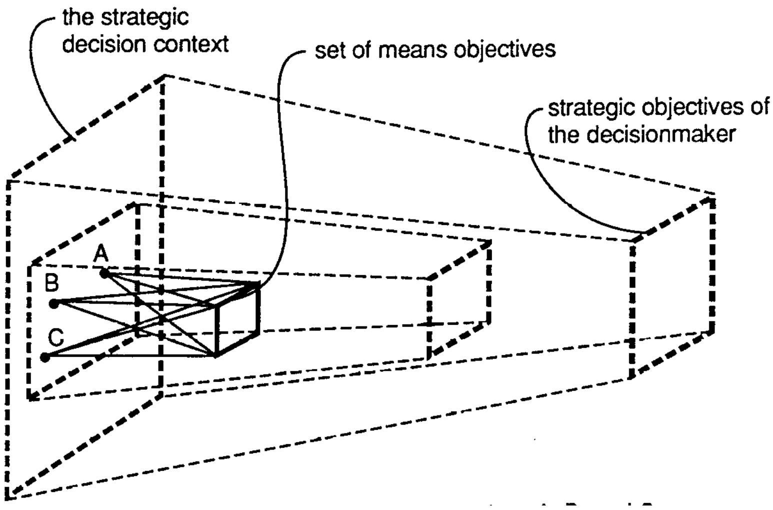


Figure 3-1. Alternative-focused thinking with alternatives A, B, and C indicated, (Keeney 1992).

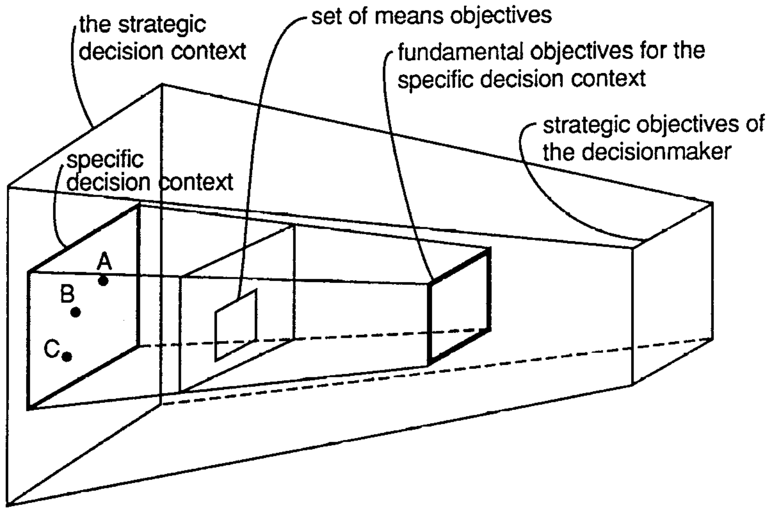


Figure 3-2. The decision frame for value-focused thinking, (Keeney 1992).

Keeny suggests that the process of framing the decision situation is likely to begin with an intuitive rough-cut that may not be very distinct from the frame provided by alternative-focused thinking. The first step of value-focused thinking is to broaden the decision situation and define it more carefully. The critical task at this stage is to define the fundamental objectives for the decision context. To do this, Keeney suggests working in two directions. The means objectives in Figure 3-2 are pushed out using a means-end logic until fundamental objectives for the evolving decision situation are found. From the other direction, one works back from the strategic objective, or from other stated sets of broad objectives, to generate fundamental objectives for the given decision. At this point one returns to the decision context to broaden it, that is, to increase the range of potential alternatives, and to match the decision context to the fundamental objectives. Essentially, the decision context is the answer to the question "What is the set of all alternatives that can affect the achievement of the fundamental objectives?"

This procedure might seem quite abstract and theoretical, but Keeney lists 10 more specific devices that can help to stimulate the identification of objectives:

1. *Use of a wish list.* The decision-makers states ideal, qualitative objectives without limitations.

2. *Use of alternatives.* Exciting or hypothetical alternatives may be a useful source of objectives. By articulating features that distinguish between alternatives (best and worst), related objectives may be discovered.

3. *Use of problems and shortcomings.* Articulating problems and shortcomings, as well as their reasons, may uncover hidden objectives.

4. *Use of consequences.* By describing the consequences of alternative actions, associated objectives are identified.

5. *Use of goals, constraints, and guidelines.* A goal is a standard that defines a specific level of achievement. Constraints define the limits within which the acceptable solutions lie. It may be useful to identify the objectives that may meet the goals or satisfy the constraints. Guidelines are less definitive than goals and constraints. They only indicate, perhaps strongly either objectives or alternatives that should or should not be considered.

6. *Use of different perspectives.* Viewing the issue from different perspectives, for example by taking the perspective of different stakeholders or viewing the present from the future, may reveal new objectives.

7. *Use of strategic objectives.* Strategic objectives are the ultimate objectives of a decision-maker. A specific decision context is only part of a large one, which is itself only a part of a still larger one, until the strategic decision context is reached. If the fundamental objectives of the broader context have been articulated, one can generate objectives for the narrower context by asking, for each fundamental objective in turn, what can be done in the present decision context to contribute to its achievement.

8. *Use of generic objectives.* Whereas strategic objectives are intended to define the concerns of a single decision-maker, generic objectives attempt to define the concerns for all decision-makers in a single decision situation. For some types of decisions, the development of generic objective hierarchies may be useful to outline the key concerns of interest. The generic hierarchy provides a basis for identifying specific objectives in a given decision situation.

9. *Use of structuring objectives.* In structuring objectives they become more clearly defined, related to one another, and related to objectives not yet identified.

10. *Use of quantifying objectives.* Quantifying objectives clarifies the meanings of the objectives, and this clarity uncovers hidden objectives and facilitates all aspects of decision-making. The process involves the identification of attributes and the construction of a value model. The identification of objectives and the specification of attributes are intertwined processes. Attributes measure the degree to which an objective is met by various alternatives. The objectives give a preference orientation with respect to these attributes. In some cases the attributes are identified before the objectives, and in other cases the objectives are identified

first. Identifying an attribute often makes it possible to better understand the meaning of a stated objective. In quantifying the objectives, specific judgements are required about value tradeoffs between attributes and about the relative desirability of different levels of given attributes. Each specific judgment provides insights about the objectives that are important for the problem.

Discussion

It seems obvious that defining one's values before starting to generate design solutions, is the ideal way of approaching a design. Finding the right objectives is crucial, more important than finding the very best alternative. The wrong objective means the work is devoted to solving the wrong problem; to designate a slightly inferior alternative as best is not nearly so serious. However, in practice, this is difficult. As was discussed in chapter 2, no building process starts out with clearly defined goals or criteria of success. The values and objectives of the decision-makers are developed throughout the design process. Edward S. Quade (Quade 1985) states:

It does not make sense for a person to make up his mind as to what he wants until he has a fair idea of what he can get and when. Thus, the investigation of objectives usually must extend beyond the problem-formulation phase. An important way in which analysis helps in clarifying objectives is that it determines the undesirable as well as the desirable consequences that follow an assumption about objectives. The decision-maker, when confronted with these consequences, can ask himself whether he is willing to accept what they imply. If not, he will have to modify his objectives.

Thus, a clear, well thought through and analytically useful statement that correctly reflects what the decision-makers really want, is rarely present in the beginning. However, some idea of what is wanted is available. Tentative objectives, specific enough to get the analysis started, can be selected. These should suggest possible ways to achieve what is wanted. The consequences of implementing these alternatives are then imagined or estimated, taking into account any constraints known to exist. The projected implications are used to reexamine the first formulation of objectives and introduce modifications.

To sum up, it is a fact that some criteria of success are needed in order to evaluate design options and choose the best strategies. It is likely that focusing on values will produce a solution that has a better chance of satisfying the needs of the stakeholders. Jumping at alternative solutions may serve to anchor the thought process, which will limit creativity. Making the values explicit may promote understanding and facilitate communication and documentation. Therefore, one should strive towards value-focused thinking prior to alternative generation and evaluation.

Before we go further, it may be useful to sort out some definitions. The terms *goals* and *targets* are often used interchangeably with *objectives* or *criteria*. A goal or target defines some desirable level of achievement with respect to an objective. Goals are a priori values or levels of aspiration that are to be achieved. Thus while objectives give the desired direction, goals (targets) give a desired level to achieve. In building design, criteria are *design issues* or *areas of concern* that demands a design response.

When a distinction between objectives and *constraints* is made, it is usually based on the idea of accepting the constraints as an absolute restriction, in contrast to an objective that may be open-ended. While the objectives suggest the alternatives, the constraints restrict them and reduce the number of possibilities that can be considered. When there are several objectives they can always be traded off at the margin if this leads to an improvement in the total utility. A constraint cannot be so exchanged, for its logical force resides wholly in its inviolability. The designers may look beyond the less rigid constraints set by the decision-maker to see if the gains resulting from relaxing them would justify the sacrifice. In the formulation and analysis of criteria in building design, neither objectives nor constraints should be treated as inviolable, but should be scrutinized from many points of view as the analysis proceeds and new possibilities emerge.

In this thesis, the word *performance criteria* will be used to designate the issues that need to be considered and optimized against in a design. The performance criteria are the basis for the evaluation of the goodness of a design option or the value of the building. The value of a building is related to how well it fulfills its purpose. The ultimate purpose of an office building may for example be to provide an environment in which the workers can feel comfortable and be able to produce goods effectively. Markus and Alexander (1997) have described a model that links the technical building system to the work environment and the objectives system of an organization. This system is illustrated in Figure 3-3. Here, the building system is depicted as a part of the total value system of an organization.

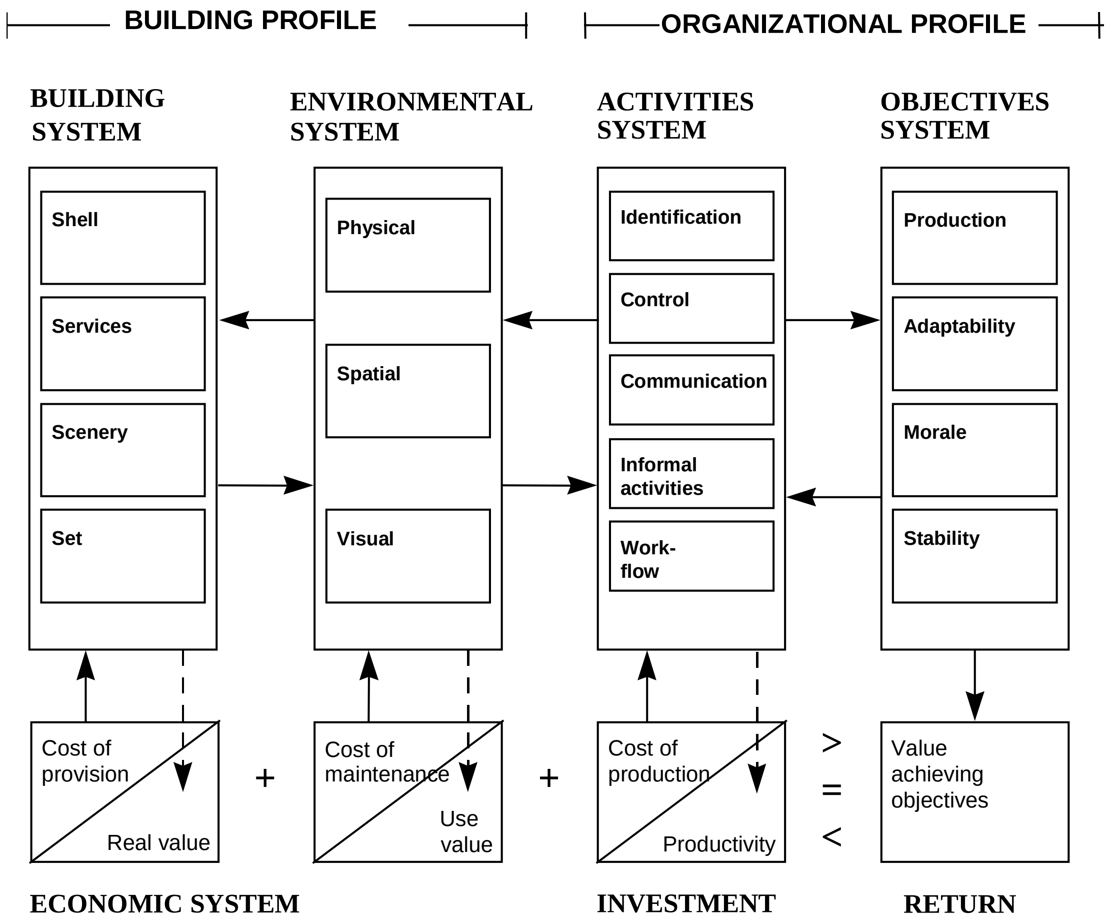


Figure 3-3. The Facilities Management Model, adapted from (Markus and Alexander 1997) by (Andresen and Blakstad 1997).

The following sections describe different methods and tools that have been used to select and organize performance criteria in building design.

3.3 Stakeholders' values in a life cycle perspective

In chapter 2, it was emphasized that the life cycle perspective is especially important when evaluating solar energy systems. This is because it is the future performance of the system that really determines its success. In order to identify a complete set of design criteria, it may be helpful to imagine the building through its entire life cycle and the needs and wishes of the different stakeholders that is associated with the building during this time, as illustrated in Figure 3-4. A stakeholder of a business is defined as any individual or group who has an interest in the business because he can affect, or is affected by the business. For example, during planning and construction of a building, the main stakeholders may be the client, the consultants, the construction workers and the regulatory authority. During occupation, the main stakeholders may be the occupiers, different suppliers of services, shareholders, etc.

Raw materials and products	Design and build	Use: Facilities management	Re-furbishment	Use: Facilities management	Demolition	→ Re-cycling
Government agencies Producers Suppliers	Government agencies Client Designers Contractors	Occupiers Suppliers ″Neighbors″	Government agencies Producers Suppliers	Occupiers Suppliers ″Neighbors″	Government agencies Consultants Suppliers Contractors	Government agencies Producers Suppliers

Figure 3-4. Life cycle stages of a building (top row) with associated key stakeholders (bottom row).

Schaltegger et al. (Schaltegger, Muller et al. 1996) give a thorough description of stakeholders and their possible interests in a project. Figure 3-5 shows an illustration of different stakeholders related to a building.

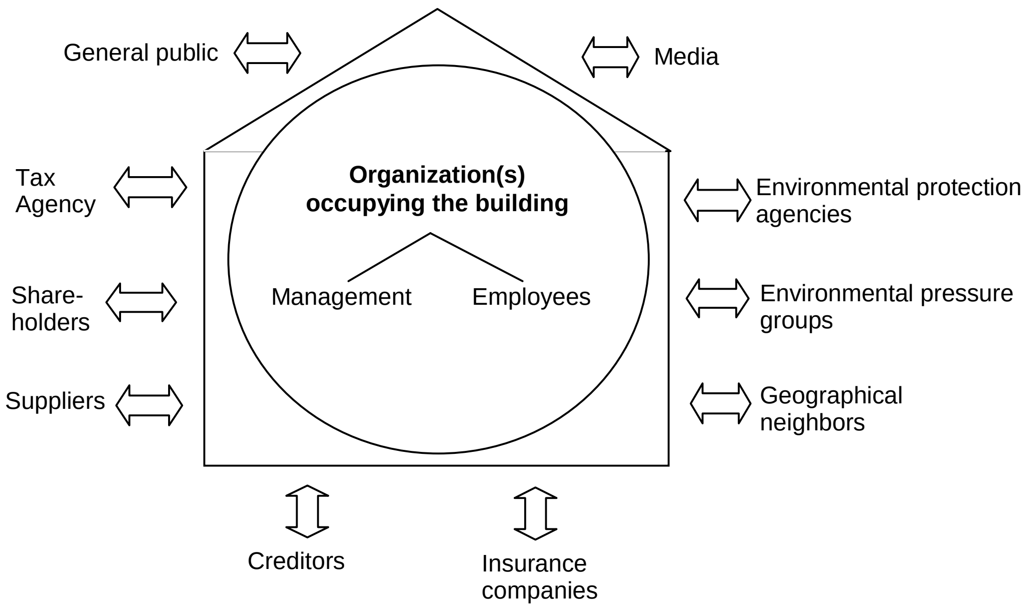


Figure 3-5. Stakeholders of an organization occupying a building. Based on (Schaltegger, Muller et al. 1996).

Dependent on the type of building process, the different stakeholders may be more or less significant. For example, in public building projects the general public would be more important than in private projects because public funds are being spent. Morton (Morton and Jaggar 1995) identifies three main groups of stakeholders of a building:

- The building occupiers (who may or may not be the owners)
- The developers
- The providers of finance

Occupiers may be any kind of commercial organization, ranging from very large businesses occupying the whole of a major building, to small businesses occupying a single floor or even just a single office.

The developers organize the purchase of the land, carry out feasibility studies to determine the most profitable form of project, arrange finance, have the building designed and built, then ultimately sold or rented out. All these functions may actually be performed by different consultant organizations, but the developer will often be the main coordinator and organizer.

The financial institutions may be banks, pension funds, or insurance companies. Two types of finance are required. First, money need to be borrowed to cover the construction period, to pay for the land, the building itself and all the associated costs of bringing a project to the stage where it can be occupied. Secondly, long-term finance is required. Developers may want to sell the property and reap their profit quickly; but at some point one organization has to be prepared to forgo cash for a long period of time – to sink money in the property, which will yield a return only over many years.

3.4 Tools and Methods for Organizing and Selecting Performance Criteria

Structuring the criteria is useful because it provides a common framework and a syntax that all the decision-makers can relate to when evaluating design options. This will facilitate communication and help the participants keep track of the design developments. The structuring process may in itself help make clear the objectives and it may help uncover criteria. A structure may also help secure that all important issues have been included. Issue-based categorization provides a structured way to handle the vast amount of information.

Numerous methodologies for organizing information have been developed and used, and still additional methods are emerging. There is no “universal” methodology that can be applied to all project types in all settings. It is also unlikely that an all-purpose methodology will ever be developed, given the changing nature of the building industry and the uniqueness of building projects. Thus, the methodologies for information management should be considered as tools that can be used as aides in the design process.

Common tools for ordering of information include checklists, matrixes, and hierarchies, see Figure 3-6. Checklists are simple listings of issues to be considered. Matrixes provide a two-dimensional framework for comparing a set of issues against another set of aspects. Hierarchies facilitate division into different levels of detail and grouping of related issues into separate entities.

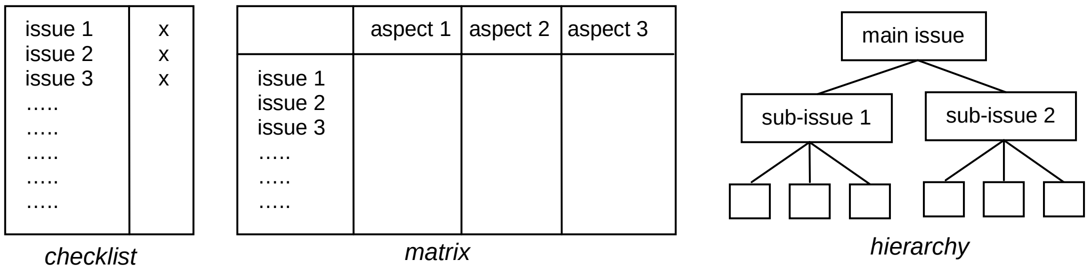


Figure 3-6. Examples of tools for organizing information.

The different tools will be further discussed in the end of this section. Following are some examples of models that have been used for structuring the criteria in building design. The models also serve to show what types of design criteria are commonly used.

The CBPR Checklist

In (Baird, Gray et al. 1996) there is a description of a checklist of factors that may influence building performance. The checklist was first developed by the Center for Building Performance Research (CBPR), New Zealand. It is structured into six main attributes: corporate, site, construction, space, internal environment and building services. Table 3-1 gives an example of a part of the checklist. The main groups of attributes are divided into sub-attributes or “factors”. Each factor is described and examples are given of items that may be investigated. The checklist may be useful to get a hint of what is important to building quality, and as a starting point to select issues for further investigation.

Factors	Description	Items
Corporate objectives	Awareness of corporate objectives, what the building's contribution is expected to be, and any implications they may have had on decisions made about the building. For example, corporate goals might include a 50 percent increase in turnover in the next 5 years and affect accommodation requirements.	Corporate mission statement Anticipated growth Production and sales targets Corporate culture Likelihood of changes Acquisitions
Serviceability	In general terms the building's capability to support the broad functions for which it is required now and in the future.	Location Total area and cost Space for people Space for other functions Adaptability if requirements change
Image	The impression the building creates for people and the extent to which the building signals its status and identity may be the influence of location, neighboring buildings, and the building itself, e.g., the color, shape, architectural features. Any particular image may be required to complement the corporate image and the activities to be carried out in the building, and by the organization, particularly where those activities involve marketing.	Status and image of location Future local development Planning developments Name, height, shape, color Details of cultural symbolism External and internal ambience Parking adjacent to entrance Entry welcoming or imposing Foyer reception area Visitors parking areas

Table 3-1. Extract from the CBPR checklist, (Baird, Gray et al. 1996).

Peña's Information Index Matrix

In his book about Architectural Programming, the American architect William Peña suggests 4 main categories of criteria; *function*, *form*, *economy*, and *time* (Pena 1987). He also suggests 3 sub-categories of each of the main categories, as shown in Figure 3-7. In the years of the oil crisis, energy was added as a fifth category (Duerk 1993).

Function	1 people 2 activities 3 relationships
Form	4 site 5 environment 6 quality
Economy	7 initial budget 8 operating costs 9 life cycle costs
Time	10 past 11 present 12 future

Figure 3-7. Four main considerations in programming, according to William Peña, (Pena 1987).

Peña (Pena 1987) presents an *Information Index Matrix* that serves as a checklist for information categories generic for each design problem. The matrix of key words is meant to be used to seek out appropriate information in the programming phase. The issue categories (function, form, economy and time) are crossed with the five steps of programming: 1) establish goals, 2) collect facts 3) uncover concepts, 4) determine needs, and 5) state the problem. Each cell contains a list of issues that need to be taken into account in order to be an appropriate information base for the design.

	Goals	Facts	Concepts	Needs	Problem
Function					
Form					
Economy					
Time					

Figure 3-8. Peña's Information Matrix, (Pena 1987).

Palmer's Model

The American architect Mickey A. Palmer used another set of categories for partitioning and organizing programming information (Palmer 1981). His matrix has one dimension consisting of Human factors, Physical Factors, and External Factors related to a design problem. The second dimension includes Ascertainments (facts about the existing state), Predictions (trends, growth potential, etc.), and Recommendations (for the future state).

	Ascertainments	Predictions	Recommendations
Human Factors			
Physical Factors			
External Factors			

Figure 3-9. Palmer's Model, (Palmer 1981).

Each of these categories has sub-categories. The cells in the matrix are specific areas for gathering, organizing, and analyzing information.

This model is criticized by Duerk (Duerk 1993) in that it blurs the lines between categories. Information about behavior is listed in both the Human Factors and the Physical Factors Categories. Codes are listed under External Factors and Human Factors, etc. Thus overlap of categories makes it difficult to keep all information organized and readily accessible.

Evaluation Matrix of Loftness et al.

In a paper on building evaluation, researchers at the Department of Architecture at Carnegie-Mellon University suggest that a total building performance evaluation should be based on six main performance areas: *functional/spatial quality, thermal quality, air quality, acoustic quality, visual quality* and *building integrity* (Loftness, Hartkopf et al. 1989). The main areas are split into sub-issues, as shown in Figure 3-10. They further advice that the performance areas should be measured against physiological, psychological, sociological and economic limits of acceptability, and presents a matrix for doing this (Table 3-2).

I. FUNCTIONAL/SPATIAL QUALITY
Based on knowledge of the building occupancies, occupancy functions, and organizational structures

A. Individual Space Layout Quality
Useable space, furnishings, layout efficiency, access, anthropometrics, ergonomics, image, flexibility/growth, occupancy controls.

B. Aggregated Space Layout Quality
Proximities, access, compartmentalization, useable space, layout efficiency, image, amenities, flexibility/growth.

C. Building Siting Layout Quality
Access, public interface/image, indoor-outdoor relationships, outdoor space layout, flexibility/growth.

D. Quality of Conveniences and Services
Sanitary, fire safety, security, transportation, electrical, telephone, information technology; flexibility/growth.

Figure 3-10. Specification of one of the six performance areas for total building performance evaluation, according to (Loftness, Hartkopf et al. 1989).

Table 3-2. Measuring performance areas against needs as described by (Loftness, Hartkopf et al. 1989).

	Physiological Needs	Psychological Needs	Sociological Needs	Economic Needs
Performance Criteria Specific to Certain Human Senses, in the Integrated System				
Spatial	Ergonomic comfort Handicap access Functional servicing	Habitability, Beauty, Calm, Excitement, View	Wayfinding Functional adjacencies	Space conservation
Thermal	No numbness, frostbite, drowsi-ness, heat stroke	Healthy plants, Sense of warmth, Individual control	Flexibility to dress with the custom	Energy conservation
Air	Air purity; No lung problems, rashes, or cancers	Healthy plants, Not closed in or stuffy, No synthetics	No irritation from neighbors, No smoke or smells	Energy conservation
Acoustical	No hearing damage Music enjoyment Speech clarity	Quiet, Soothing, Activity, Excitement, "Alive"	Privacy Communication	First-cost conservation
Visual	No glare, Good task illumination, Wayfinding, No Fatigue	Orientation, Cheerfulness, Calm, Intimate, Spacious, "Alive"	Status of window Daylit office "Sense of territory"	Energy conservation
Building Integrity	Fire safety; Structural strength + stability, Weathertightness, No outgassing	Durability Sense of stability Image	Status/appearance Quality of construction "Craftmanship"	Material/labor conservation
Performance Criteria General to All Human Senses, In the Integrated System				
	Physical Comfort Health Safety Functional appropriateness	Psych. comfort Mental health Psych. safety Esthetics Delight	Privacy Security Community Image/Status	

The House of Quality

The *House of Quality* is a matrix-based tool which is part of a method for specifying product requirements called *Quality Function Deployment – QFD* (Akao 1990). The method is widely applied in the development of consumer products, but has not gained widespread use in the building industry (Huovila 1999).

In the House of Quality, all customer requirements are identified and weighted, and the relationships between these requirements and the technical parameters of the total product are analyzed, see Figure 3-11. Information from the House of Quality is first of all an input to the specification of a new or modified product. Based on the evaluation of priority of technical parameters for improvements in the product, and the analysis of competing products, the project team can prioritize between different projects with basis in customer requirements. In the next stages of the QFD process, relationships between the important technical parameters and the product system are analyzed stage by stage, from functions and organs (subsystems), components and processes, and finally manufacturing and assembly. The QFD method is of special importance in the early phase of the product development, before too much cost has been allocated to a special product concept.

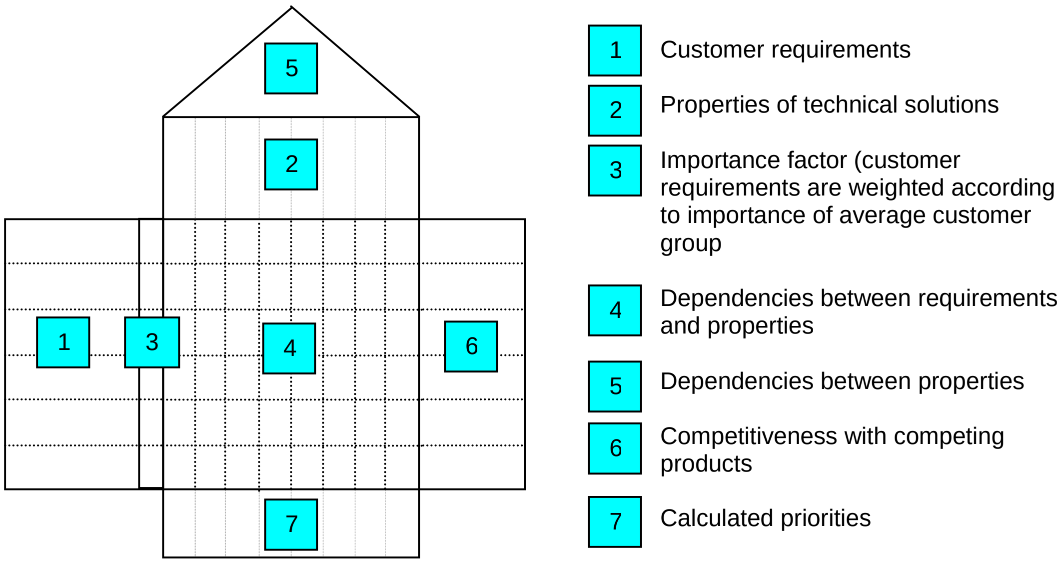


Figure 3-11. The House of Quality.

The QFD approach has been demonstrated in a pilot building project in Finland (Nieminen, Houvila et al. 1998), (Huovila 1999). Here, the House of Quality was used to set project and design objectives in a housing development project called “Villa 2000”. The House of Qualities matrix is shown in Figure 3-12. The weights of the design team are listed in the rightmost column (importance factors between 1 and 5). The correlation between the properties (in the top row) and the requirements (in the 2nd column) are modeled by priority weights (0,1,3,9 – the higher number the higher priority). The priority weights and the importance factors are multiplied for each requirement, and then added to obtain the weight factors at the bottom of the matrix. After filling in the matrix, the group re-considered the weight factors, and it was decided that six of the most important factors were to be processed further.

	Properties / Requirements	**adaptability**	**resale value**	**indoor conditions**	attractiveness	**economy**	autonomy	**environmentally friendly**	future oriented	habitability	respond to the environmen	good indoor climate	**constructability**	identity	**total ecology**	**architecture**	simple user interfaces	re-usable fair house	transferability	dismountability		**Importance factor (P1)**
functionality	**utilisability**	**9**	**9**	**9**	9	**3**	9	**3**	0	9	0	9	**0**	1	**1**	**0**	9	3	1	0		**5**
	adaptability	**9**	**3**	**0**	9	**3**	1	**9**	3	9	0	0	**1**	1	**9**	**0**	1	9	9	9		**2**
	Maintainability	**3**	**3**	**3**	3	**9**	9	**9**	0	9	0	3	**0**	0	**9**	**1**	3	1	1	1		**2**
environmental	use	**9**	**3**	**9**	3	**9**	9	**9**	1	1	9	9	**0**	0	**9**	**0**	0	0	0	0		**4**
loading	construction	**0**	**0**	**0**	3	**3**	0	**9**	0	0	0	0	**9**	1	**9**	**1**	0	9	9	9		**2**
resource	**energy**	**9**	**3**	**9**	3	**9**	9	**9**	9	0	9	9	**0**	3	**9**	**0**	0	1	1	1		**5**
use	*water*	**9**	**1**	**0**	1	**3**	9	**9**	3	1	0	0	**0**	0	**3**	**0**	1	0	0	0		**1**
	materials	**3**	**9**	**9**	3	**9**	1	**9**	9	9	0	9	**9**	9	**9**	**3**	0	9	9	9		**1**
life	investment cost	**9**	**9**	**3**	3	**9**	3	**0**	0	0	3	3	**9**	1	**0**	**0**	1	3	3	3		**3**
cycle	operating cost	**9**	**9**	**1**	3	**9**	9	**9**	3	0	3	1	**0**	3	**3**	**9**	9	3	3	3		**4**
costs	maintenance	**9**	**9**	**3**	9	**9**	9	**9**	9	0	9	3	**0**	3	**3**	**9**	3	3	3	3		**2**
indoor	ac oustical comfort	**9**	**9**	**9**	9	**0**	0	**0**	9	9	0	0	**3**	3	**0**	**9**	0	0	0	0		**2**
environment	thermal comfort	**9**	**9**	**9**	9	**0**	0	**3**	9	9	9	9	**3**	3	**0**	**9**	3	0	0	0		**3**
	daylight	**9**	**9**	**9**	9	**3**	9	**3**	9	9	9	0	**3**	9	**1**	**9**	1	0	0	0		**4**
	air quality	**3**	**9**	**9**	9	**0**	0	**3**	9	9	9	9	**9**	9	**1**	**0**	0	0	0	0		**5**
architecture	Architecture	**9**	**9**	**9**	9	**9**	3	**0**	9	9	3	0	**9**	9	**0**	**9**	1	3	3	3		**3**
	Weight factor (P1)	**393**	**355**	**322**	307	**285**	273	**258**	250	248	246	241	**182**	180	**179**	**169**	118	112	102	97	0	**4317**
	Weight factor %	**9%**	**8%**	**7%**	7%	**7%**	6%	**6%**	6%	6%	6%	6%	**4%**	4%	**4%**	**4%**	3%	3%	2%	2%	0%	**100%**
	votes	**4**	**1**	**3**		**2**	1	**3**			1		**2**		**4**	**4**	1	1				
	Selected	**X**		**X**		**X**		**X**					**X**		**X**	**X**						

When you select properties, use capital X

Figure 3-12. House of Quality matrix for the Villa 2000 project (Huovila 1999).

The House of Quality is useful for cross-matching the properties of a physical solution with the requirements in order to find what properties are important to focus on. In this way, it may help specifying promising alternatives. The procedure is fairly comprehensive, and might be quite time-consuming. It seems necessary that the approach be simplified in order to be used in the building design process. The concept of linking properties and requirements in order to find what issues to focus on, is interesting.

Firmness, Commodity and Delight

The criteria of *firmness*, *commodity* and *delight* have been the three major factors of consideration in architectural design since the famous translation of Vitrivius by Sir Henry Wotton in the late 18th century. Firmness includes considerations of structural strength and durability. Commodity relates to physical and psychological comfort, including value and usefulness. Delight has to do with pleasure for all senses. Figure 3-13 shows a hierarchy of these criteria with sub-criteria presented by (Duerk 1993).

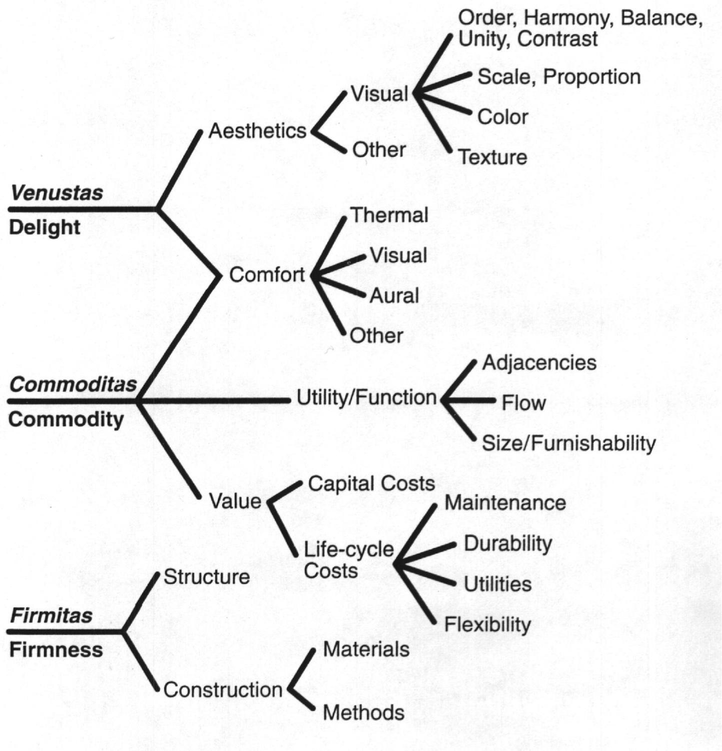


Figure 3-13. Architectural design considerations according to the traditional model of firmness, commodity and delight, ordered into a hierarchy. From (Duerk 1993).

Alexander's Hierarchy of Subsets

In the mid 60's Christopher Alexander proposed that the designer should make a hierarchy of ideas and isolate the variables into subsets that have little influence on other sets of variables. The process of describing the problem holistically begins by demonstrating the problem into a hierarchy of classes by proceeding from the general to the specific, as illustrated in Figure 3-14. The variables that have an effect on each other are grouped so that, to the maximum extent possible, their variations within the subset will fully describe the problem at the lowest level of division and simultaneously have a minimal effect on the variables in a different subset, Figure 3-15. This arrangement will give the design team the information in a format that can easily be manipulated but not easily misunderstood.

Alexander's model has been criticized, not least by himself. The criticism is mainly concerned with theory questions, for example the assumption that there is a set of requirements that can be listed at the start of the design process, and that the listed requirements are of equal value (see the discussion in chapter 2). Also, the idea of breaking down the problem into constituent parts have been viewed as a contradiction of the integrated design approach (Lawson 1997). Nevertheless, the theory of hierarchical structuring of systems and sub-systems into more or less independent units have been taken up in many fields, for example in decision analysis and systems engineering.

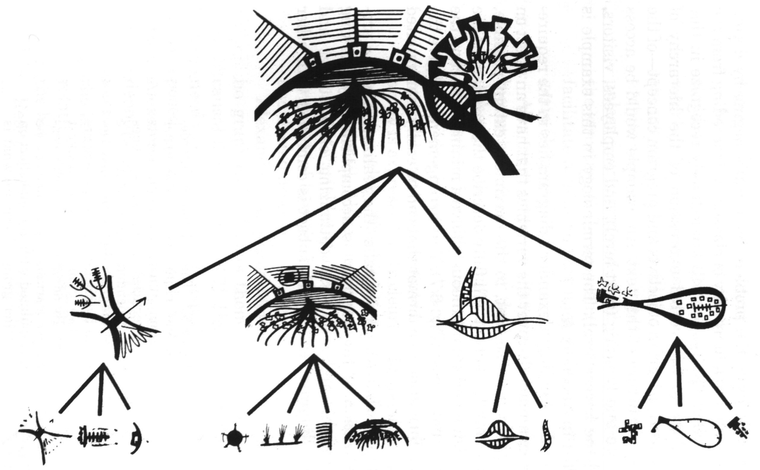


Figure 3-14 Alexander's hierarchy of subsets. Each icon in the branching diagram is the resolution of a set of isolated interdependent variables. From (Alexander 1964).

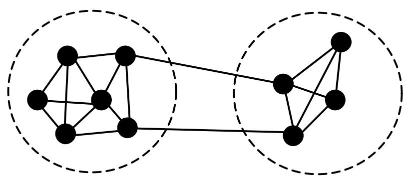


Figure 3-15. The isolation of interdependent requirements. The interdependent requirements (the vertices) are connected with lines. The requirements are isolated into two groups at their weakest links. By doing this, the richly connected variables may be manipulated with minimal effect on the other groups. From (Alexander 1964).

List of typical design criteria by Kirk and Spreckelmeyer

The American Architects Stephen Kirk and Kent Spreckelmeyer argue that *"although a unique set of criteria will characterize each decision problem, it is likely that a uniform and repetitive set of concerns will be present, in one form or another, in all design problems"*. Thus, they present a list of typical design objectives that can be used as a basis for selecting criteria to focus on, see Table 3-3.

Table 3-3. Typical design objectives according to (Kirk and Spreckelmeyer 1993).

Design objective	Definition
Image	The visual concept of the building and the way in which the building attract attention to itself. The form of the building and the degree to which it acts as a symbol for the company.
Community	How the building an its site project a "good neighbor" identity in terms of safety, security and privacy.
Functional efficiency	The degree to which the building is able to respond to the work process and flow of people, equipment, and materials.
Security	The degree to which the building can segregate sensitive functions from one another and prevent the entry of people to restricted areas.
Expansion	The ability of the building to grow to meet projected changes in the work process without disturbing existing building functions.
Flexibility	The degree to which the building plan can be rearranged to conform to revised work processes and personnel changes.

Technical performance	How the building operates in terms of mechanical systems, electrical systems, and industrial processes.
Human performance	How the building provides a physically and psychologically comfortable place for people to work and live.
Energy conservation	The degree to which the building is able to conserve energy resources through construction, site orientation and solar design.
Life-cycle costs	The economic consequences of the building in terms of initial capital investment and long-term operating costs.
Others	To be defined for specified project requirements.

Hierarchy of Performance Criteria in the GBC'98 Project

In the international project "Green Building Challenge'98" (see chapter 6.2) six main performance areas were identified: *Resource Use, Ecological Loadings, Indoor Environmental Quality, Process, Longevity,* and *Context* (Cole and Larsson 1998). An extract of the Resource Use performance area is shown in Figure 3-16. *Contextual issues* relate to site selection, building location and proximity to amenities. *Process* includes issues that relate to the structuring of the design team as well as operation and maintenance practices. The main performance areas contain *performance categories* at the next level of detail, followed by *performance criteria* and *performance sub-criteria* at the lowest level. Altogether there are 4 levels of criteria, adding up to a total of 120 criteria at the lowest level. In the early design stage, this level of detail will probably be too much to handle. The GBC'98 framework is primarily aimed at assessing the performance of existing buildings.

SECTION ONE: RESOURCE CONSUMPTION

R1 ENERGY

R1.1 Embodied energy for initial production

R1.2 Embodied energy consumption for recurring production

R1.3 Operating energy consumption

R1.4 Decommissioning energy

R1.5 Peak demand

- R1.5.1 Peak electrical demand
- R1.5.2 Peak natural gas demand
- R1.5.3 Peak heating or cooling demand (if district heating)

R1.6 Thermodynamic matching of fuel type and end use

R2 LAND

R2.1 Initial ecological significance and scarcity of land used

R2.2 Efficiency of land use

R2.3 Maintenance of biodiversity and ecology on building site

Figure 3-16. Extract from performance area "Resource Consumption" in the GBC'98 framework, (Cole and Larsson 1998)

Discussion

Checklists may be useful as a starting point for identifying and selecting relevant criteria. However, it is hard to imagine a checklist that includes all possible issues that are applicable for all types of building projects. Thus, there is always the danger that the checklist does not include all the issues that are relevant for a specific case. Another problem with checklists is that they do not simplify overview very much.

Grouping of related design topics is possible, but the checklist offers limited possibilities for mapping more complex interactions between criteria.

Matrixes are useful instruments to visualize interdependencies between pairs of issues. However, multi-level links are hard to implement within this framework. Another problem with matrixes is that they may lead the decision-maker to think that he has to fill in every window, even though the information is not relevant. This may lead to the generation of information that is not needed.

The hierarchical structure is more suitable to keep track of multiple interdependencies as well as different levels of detail. The hierarchy may easily be segregated into parts, so that one can work with one branch at a time. With a hierarchy, it is possible to keep the overview, and at the same time have the possibility of going into detail. Hierarchies are also flexible; additions or reductions to a well-structured hierarchy may easily be implemented. Thomas L. Saaty even claims that hierarchical structuring appears to be an innate method of operation of the human mind (Saaty 1996). When presented with a multitude of elements which comprise a complex situation, the mind aggregates them into groups, according to whether they share certain properties.

In the context of this thesis, the main purpose of structuring the criteria is to form a basis for a formal evaluation process. In this respect, hierarchical representation of a system is well suited because it describes how changes in priority at upper levels affect the priority of elements in lower levels. A hierarchy allows us to focus on one part at a time, without loosing the interactions or the overview. Hierarchies are also well suited for mapping the theory of value focused thinking described by Keeney. At the top of the hierarchy is the main strategy or fundamental objective. Below, the means objectives may be derived, from which the alternatives will spring. In the next chapter, a further investigation of how to structure criteria in hierarchies is given.

3.5 Criteria in Hierarchies

Thomas L. Saaty gives the following description of a hierarchy (Saaty 1996):

A hierarchy is an abstraction of the structure of a system to study the functional interactions of its component and their impact on the entire system. This abstraction can take several related forms, all of which decent from an apex (overall objective), down to the people who influence these forced, down to the objectives of the people and then to their policies, still further down to the strategies, and finally, the outcomes which result from these strategies.

Thus, a hierarchy becomes more and more detailed as one moves down from the top. The objectives at the top of the hierarchy are usually quite abstract, such as “an efficient building” and become more specific as one follows the hierarchy down. It is usually recommended to go down the hierarchy until a measurable goal is reached. Many authors suggest to limit the number of criteria at each branch level in the hierarchy to 7. This is based on Miller’s theory (Miller 1956), that suggest that 7 ± 2 represents the greatest amount of information that an observer can give about an object on the basis of an absolute judgment.

Within the field of decision analysis, value hierarchies are often called decision trees. In this field, two distinct approaches to structuring value hierarchies are described; *the top-down* and the *bottom-up* approaches. The top-down approach is objective led, whilst the bottom-up approach is alternative led. In the *top-down* approach one starts with defining the general values relevant to the problem. Next, one defines what the initial value categories mean by using more specific value dimensions. The method of value-focused thinking described by Keeney (section 3.2) is an example of a top-down approach. Keeney gives a summary of advantages of the top-down approach that may be used as guidelines for how to develop and structure the hierarchy (Keeney 1992):

1. The higher-level objectives hierarchy relate to fairly general concerns, such as the environment, economics, health and safety, and flexibility. Consequently, they can be identified relatively easy.
2. Higher-level objectives provide a basis for specification of lower-level objectives.
3. A hierarchy helps identify missing objectives, since logical concepts of the specification process can fairly easily identify holes in the hierarchy.
4. Situations where redundancy or double-counting might occur can often be identified with the logic of an objective hierarchy.
5. It is easier to identify attributes to measure the achievement of more specific (lower-level) objectives than of more general (higher-level) ones.
6. The attributes for a lower-level objective collectively indicate the degree to which the associated higher-level objective is achieved.
7. The complete set of lowest-level attributes for a fundamental objectives hierarchy provides a basis for describing the consequences in the decision problem and for assessing an objective function for the problem.

Von Winterfeldt and Edwards (von Winterfeldt and Edwards 1986) give a list of questions that may be used to check the structure of the hierarchy:

1. Does the subdivision really help explain the meaning of the general value category, or are the value dimensions related in some other way (e.g. functional relation, means-end relation)?
2. Is the proposed subordinate value dimension unique to the superordinate value being explicated, or is it linked to others?
3. Is the list of value dimensions exhaustive?
4. Are some value dimensions redundant or partially redundant?

The *bottom-up* approach starts with identifying the characteristics that distinguish the objects of evaluation. The idea is to identify value-relevant characteristics and to synthesize them in order to get higher order values. The approach starts with a very large list of aspects, characteristics, or indicators of the outcomes of the options under consideration. Von Winterfeldt and Edwards suggest some questions that may be posed in order to select or define value-relevant attributes from such lists (von Winterfeldt and Edwards 1986):

1. Does the decision-maker have meaningful preferences for different degrees of an attribute?
2. Can the alternatives be distinguished on the basis of that attribute?

3. Are evaluations of some attributes dependent on other attribute values?

The first question determines whether an attribute is value relevant. For example, sulfur dioxide pollution may appear on the initial list for comparing alternative power plants, but the decision-maker may find it hard to say much more about the pollution level than “less is better”. The real preferences may concern the health effects of sulfur dioxide pollution.

The second question determines whether the attribute is relevant to the evaluation. For example, if all possible options score the same on a given attribute, that attribute is irrelevant and should not be included in the list.

The third question that von Winterfeldt and Edwards describe, determines whether the attributes are *judgmentally dependent*. Two attributes are judgmentally dependent if the evaluation of an alternative with respect to one attribute depends on how the alternative performs with respect to the other. For example, in judging the quality of a rifle, accuracy and range are two important attributes. Yet if a rifle is very inaccurate, one may not care about its range. Consequently, the evaluation of the relative benefits of a range depends on the relative accuracy of the rifle.

Keeney and Raiffa propose some general criteria that are relevant for examining the structure of a hierarchical tree (Keeney and Raiffa 1976):

- Completeness
- Operationality
- Decomposability
- Absence of redundancy
- Minimum size

Completeness requires that all relevant values be included in the superstructure of the hierarchy and that the substructure completely defines the higher level values. Operationality requires that the lowest level values or attributes be meaningful and assessable. Decomposability means that the attributes can be analyzed one or two at a time, that is that they are judgmentally independent. Absence of redundancy means that no two attributes or values mean the same thing. Minimum size refers to the necessity of keeping the number of attributes small enough to manage. These requirements conflict. Operationality often requires further decomposition, thus increasing the number of attributes. Completeness may lead to redundancy, since true value independence is often an unattainable ideal. Thus, a trade-off between these criteria is often necessary.

In situations where a number of alternatives are readily available for consideration, the bottom-up approach is an effective way of getting going. By using a number of techniques designed to promote thinking (for example brainstorming) one can usually rapidly generate many potentially relevant criteria. However, there is the danger of becoming too constrained by the alternatives. As argued in section 3.2 (value focused thinking), a top-down approach should ideally be opted for. In practice, a combination of the two approaches is probably needed. The key point is to start out wide with a generic, all embracing value hierarchy (with fundamental objectives as described by Keeney, see above), then narrow it in by focusing on what issues are relevant for the specific case. Then, many irrelevant issues will cancel out, and one will hopefully end up with a hierarchy that is manageable. In this way, the danger of omitting important issues is limited, as one has to argue and document why some criteria are deleted from the all-embracing hierarchy. When potential solutions begin to emerge, these may be used to upgrade the value hierarchy, adding, removing and refining criteria. In this way, one moves up and down the hierarchy in an iterative process alternately focusing on values and alternatives.

3.6 Conclusions

Values are the basis for evaluating the goodness of a proposed design solution. Therefore, focusing on the values of the stakeholders is essential for the success of the project. Ideally, the best way of approaching a building design is to focus on the values before evaluating alternative solutions. This will broaden the solution space and encourage creativity, and thereby the increasing the possibility of finding the best solution. In practice, though, the processes of generating alternatives and specifying objectives will be intertwined. This is because it is difficult to give very specific goal statements before one has a clear picture of what is possible or feasible. The initial, vague objectives will be revised and refined as the design evolves.

Sorting the values into issue-based categories makes it easier to handle the vast amount of information that is important for holistic building design. Grouping together items in a common framework using a consistent terminology will reduce misunderstandings about meaning. This may facilitate communication among members of the design team, as well as to regulatory agencies and the general public.

In order to be useful in a formal evaluation, the criteria must be selected in a manner that decomposes a problem statement into independent measurement scales. There are a number of checklists available that may be used to get ideas of what criteria to include and how to structure them. A hierarchical structure seems to be well suited for organizing the criteria. Also, people seem to find such a structure natural for organizing information. The hierarchy allows for organizing the problem into different levels of detail. In this way it is possible to keep the overview while at the same time be able to see the details. Multi-level interdependencies may be modeled, and the hierarchy may easily be extended or reduced as new information and knowledge emerge during the design process.

One day Alice came to a fork in the road and saw a Cheshire cat in a tree. Which road do I take? she asked. Where do you want to go? was his response. I don't know, Alice answered. Then, said the cat, it doesn't matter.

- Lewis Carroll

4 Generation of Alternatives

The generation of good alternatives is important if the design process is to be effective. If alternatives are generated without careful consideration, much time will be wasted on evaluating solutions that are far from fulfilling the goals of the stakeholders. Generating alternatives is above all a craft, an exercise of creativity and experience. Therefore, it is hard to specify a formal method for approaching it. However, there are a number of techniques that have been proposed as aids in generating alternatives. Some of these will be briefly described in section 4.1. In addition, the following general guidelines are given:

- It is not possible to do a careful evaluation of all possible solutions. However, it may be wise to start out with a fairly wide variety of solutions that will test the extremes of the design-objective definitions. This reduces the risk of overlooking good ideas. In the beginning, one may encourage inventions and unconventionality, and it may be fruitful to look beyond the less rigid constraints to broaden the scope of study outside the limits that were initially set by the client. The use of multidisciplinary groups in design, e.g. composed of the owner, user, architect, engineer, and builder, is likely to generate a much wider range of ideas than from an individual working alone.

- The many alternatives that are considered initially cannot be investigated in detail. It would be too costly and time-consuming. Only simple evaluations should be carried out at this early stage. Some kind of screening is needed to select the alternatives that are most promising for the next stages of investigation. The screening could be based on expert judgement, evidence from past cases, or simple models. Examples of techniques that can help the screening process are given in chapter 6 (Performance Evaluation).

- The initial, rough evaluation will in turn lead to the specification of more precise design criteria which can be used in the next stage of more detailed evaluations. The stages that follow the initial scrutiny may include an increasing amount of quantitative analysis. The last stage of the selection procedure should investigate relatively few alternatives, but in considerable detail.

- Including a "base case" or a "do-nothing" alternative in the set of alternatives might be useful. By comparing the effects of other strategies to the base case it is possible to determine if a proposed strategy will be better, and how much of an improvement can be expected. A "do-nothing" alternative is common practice in environmental impact analyses.

An effective process of generating alternatives is also dependent on a structured management of information. A structure based on value focused thinking as described in chapter 3, will provide this.

4.1 Techniques for generating alternatives

This section includes a brief description of some techniques that have been proposed as aids in generating alternatives. The description is mainly based on (Kirk and Spreckelmeyer 1993) and (Kumlin 1995). The survey is by no means meant to prescribe how the task of generating alternative should be carried out, it is just included to show some possible ways of going about the task.

Brainstorming

Brainstorming is a technique that originates from Alex F. Osborn (Osborn 1957) and is defined as *an organized way to allow the mind to produce ideas without getting bogged down in trying to judge the value of those ideas at the same time.* It is based on the stimulation of one person's mind by another's. A typical brainstorming session takes place when a group of people sits around a table and spontaneously generates ideas designed to solve a specific problem. During the session, no attempt is made to judge or evaluate the ideas. Evaluation takes place after the session has ended. Normally, a group leader records each idea offered by the team, sometimes with the assistance of a tape recorder. The main guidelines of brainstorming may be summarized as follows (Dell'Isola 1997):

- Rule out criticism. Withhold adverse judgment of ideas until later. If nothing good can be said about an idea, nothing should be said.
- Generate a large number of possible solutions. Set a goal of multiplying the number of ideas produced in the first rush of thinking by five or ten.
- Seek a wide variety of solutions that represent a broad spectrum of attacks on the problem.
- Watch for opportunities to combine or improve ideas.

Delphi

The Delphi technique is an approach for eliciting opinions from a group of experts. It's prime motivation is the desire to avoid the psychological problems of face-to-face discussions that can be detrimental to establishing a reliable group consensus. A Delphi process involves a series of successive questionnaires, where, in each questionnaire after the first, the respondents receive feedback information about the outcome of the preceding round without learning which option was contributed by which particular respondent. The method was first designed by Dalkey and Helmer to be used in a military estimation problem that arose at the Rand Corporation in the early 1950's (Gordon and Helmer 1964). Since then it has been employed in several thousand cases all over the world, covering divergent subjects such as educational reform, long-range corporate planning, the future of medicine, assessments regarding the quality of life, etc. (Linstone and Turoff 1975). Kirk and Spreckelmeyer (1993) describes an application of the Delphi technique to the identification of design options for a health care center, as follows (shortened from the original description):

The multidisciplinary team consisted of a group leader, a client representative, the architect, a structural engineer, and a mechanical engineer. A list of functions the building is expected to satisfy is provided to the team along with an estimate of costs. After design requirements are reviewed, each participant is asked to list ideas for reducing the floor-to-floor height. Each participant then completes a worksheet indicating his ideas for solving the problem. Afterwards, the group is assembled and all ideas (42 in total) are listed on a flip chart for group discussion. As group discussion begins to organize random ideas into packages, certain ideas are judged as having significantly more potential than others.

The second cycle of the Delphi begins with individual team members excluding ideas from further consideration and developing new alternatives. Team members discuss a list of alternatives that meet functional criteria.

By the third and final iteration, various team members begin to agree on key points. The structural engineer proposes using opening web trusses in lieu of spandrel beams. The mechanical engineer balances air distribution over the space, taking care to integrate this system into the structure. The architect suggests that a nine-foot flat ceiling be maintained for future flexibility within the health care center.

Manipulation

In manipulation techniques, the creative effort is directed towards seeing commonplace elements in a totally new way. The specific definition of the problem is kept vague to avoid a premature or predetermined solution.

The Gordon Technique (Gordon 1961) involves a free-flowing discussion of ideas regarding a loosely defined problem. No one but the group leader knows the exact nature of the problem. A subject is selected that relates to the real problem as nearly as possible. For example, the group might discuss “how to store things”, while the real problem is to find a solution to a warehousing problem for a manufacturing company. The Gordon technique seeks to avoid the pitfalls of an ordinary brainstorming session; the feeling of the participants that they have found the “correct” solution, and therefore there is no need to look for any other solution to the problem.

Synectics is another formalized creativity technique that has been attributed to William J.J. Gordon (Gordon 1961). It encourages the use of metaphors and analogies to spawn inventiveness in problem solving. Synectics, from the Greek *synektik*, means joining together different and apparently irrelevant elements to form new and effective ideas and schemes. The purpose of synectics is to multiply ideas by stimulating the imagination through various types of analogies. Gordon described four types of analogies: *symbolic*, *direct*, *personal* and *fantasy*. *Personal analogy* injects individual identification into the problem situation in order to experience the effects under study. A *direct analogy* compares similar facets and procedures of dissimilar objet. For example, the cooling system of a dwelling might be designed to act in the same way as the human body cools itself. *Symbolic analogy* uses the actions and structure of one object to create the image of something completely different. *Fantasy* is the use of conscious self-deceit by unrestrained imagination to explore a situation. Existing laws and rules are temporarily suspended.

Bionics and biomechanics are techniques that look to nature for ideas. For example, the structure of a high-rise building design may be analogous to a tree and its roots.

Pattern

The opposite of the purposeful creation of vagueness is the establishment of an orderly way of going about identifying and crating ideas. Several techniques encompass this systematic approach:

Checklists contain a number of clues to be compared against the problem definition in order to identify new possibilities and design options. Checklists range from specialized to generalized. Flanagan et al. show an example of a specialized checklist for preliminary selection of floor finishes. The criteria are listed in one dimension, while the alternatives are listed in the other dimension, see Table 4-1. Wherever an alternative meets a criterion, a check mark is inserted at the intersection. Also, there is a column for checking whether the criterion is a requirement for the actual function.

Table 4-1. Checklist for preliminary selection of floor finishes, adopted from (Flanagan, Norman et al. 1989).

Criteria	Requirement	Ceramic Tiles	Vinyl Tiles	Granolithic	Marble
Abrasion resistance	x	x		x	
Acid resistance	x	x	x		
Alkali resistance					
Anti-static	x	x			
Closed pores	x				
Fire resistance	x	x	x		x
Frost resistance					x
Slip resistance					x
…..	x				x
	x	x			

Checklists can be both helpful and obstructive. A list that is not open-ended can restrict thinking. Checklists are aimed at solving a specific problem. At the very least they may assure the designer that successful approaches used in the past have been considered for the present situation.

Morphological analysis is a structured way to list combinations of characteristics to yield new alternatives. A visual model helps in cross-relating or seeing combinations of characteristics. For example, the following matrix of lighting systems may be used:

Table 4-2. Cross-relating attributes of lighting systems, from (Kirk and Spreckelmeyer 1993).

LIGHTING TYPE	LENS TYPE			
	Prismatic	Polarized	Parabolic	Indirect
Incandescent	x			x
Fluorescent	x	x	x	
Mercury vapor			x	

Attribute listing involves listing all the attributes that characterize and item under study. The team then tries to modify the attributes to yield new alternatives. For example, the attributes of venetian blinds may be changed as follows:

- change horizontal slats to vertical slats
- change horizontal pivoting to vertical pivoting
- change pulley cord to twisting on a fiberglass rod
- etc.

Pattern language was developed by Christopher Alexander at the University of California at Berkeley (Alexander, Ishikawas et al. 1977). A set of prototypes for a particular building is identified and the best is selected for the review team. Simple sketches and a few words illustrate each prototype. The sketches or diagrams are grouped into patterns that represent the building element. The last step is manipulation of patterns to meet the owner-user requirements, climatic conditions, and urban context.

4.2 Conclusions

The generation of alternatives is an iterative process that is closely related to the tasks of problem formulation and evaluation. The evaluation of alternatives may generate new alternatives or objective, or it may alter the objectives. The process of generating alternatives is mainly a craft, and it is not possible to give a general recipe that will fit any project. However, it may be made more effective by using some formal aids, especially if inexperienced participants are involved. The success of the alternative generation process relies heavily on the problem formulation. A well-formulated and organized value structure that reflects the needs and wishes of the building’s stakeholders, is a prerequisite for this.

It is better to be roughly right than exactly wrong.

5 Performance Prediction

5.1 Introduction

The second design task that was identified in chapter 2, is performance prediction of potential solutions. Performance prediction is carried out in order to find out how well a proposed solution satisfies the objectives. In this respect, it is the basis for evaluating and choosing design solutions. Thus, the performance prediction has to produce means to measure the relative goodness of a design with respect to the needs and wishes of the decision-makers. Also, due to constraints on time and resources, the right level of detail has to be found. In section 5.2 the concepts of *optimizing* and *satisficing* are discussed. These represent two contradictory ways of going about performance prediction. Section 5.3 deals with tools and methods that are used in predicting the performance of buildings and solar energy systems in the design phase. Since this was also an issue of chapter 2, this section only includes a discussion of different types of prediction and the level of detail. Section 5.4 then deals with how to present the results in an unbiased and clear manner. In section 5.5, the findings of the previous chapters are summed up, and conclusions are made.

5.2 Optimizing and Satisficing

In principle, one could think that the ideal way of doing a performance prediction would be to construct a model that incorporates all parameters and characteristics that determines the optimum solution. One could then input all feasible values for environmental parameters and product characteristics and out comes the optimum, i.e. the best possible solution. However, such an approach poses several problems. Thorbjoern Mann (Mann 1992) gives an excellent discussion of the concept of optimization, which is briefly summarized below:

Optimization means simply the process of finding the best solution. The concept seems quite straightforward, but its practical implications are not. What is the "best" solution? How is it measured? Measurements about what is good and bad inevitably involve subjective judgments, which mean that people will tend to have different opinions about it. How can we achieve agreement about measurement as a condition for making decisions?

Let us assume that those persons involved in a planning or a design situation somehow do agree upon a common measure of performance by which one can tell which of two solutions is "better" than the other. Then, they can find the value of that performance variable for each solution, compare the values, and decide which *solution has the "higher" value of that performance measure. Doing this, they will have achieved one of the necessary conditions for optimization: there must be an agree-upon measure of performance such that each solution will be described by just one value of that variable.*

However, this is just the beginning of the problem. The "optimum" is not necessarily just the better of the two alternative solutions that were compared. But if we threw the issue wide open and said "optimal" is to mean the solution with the highest value of the performance measure out of all possible solutions, we would lose our basis of agreement, unless we had actually examined all those possible solutions and determined their respective performance. This is the second of the conditions for any meaningful talk about optimization: a well-defined solution space with well-defined constraints.

However, if we continue in our (some would say reckless) quest for optimality, we should know about a few other terms and associated pitfalls. For their discussion, it is helpful to visualize the solution space as a hilly landscape in which the performance measure forms the third dimension, that is, the height or elevation, see the figure below. The highest mountain in this landscape is the global optimum. There are other, smaller mountains; these are called local optima. The first potential source of error is that our efforts of optimization would result in finding only a local and not the global optimum.

Even worse is another possible and very common error, that of sub-optimization. The mountain landscape consists of layers of judgment scores. The layers correspond to the various sub-aspects that together make up the overall judgment score or overall performance measure. Because some aspects are more important than others, and also may be easier to measure, the evaluation may be looking at those measures to the exclusion of others. Thus, an unspoken assumption is made that the highest hill or global optimum also will have the highest invisible layers of the subsequent underneath it.

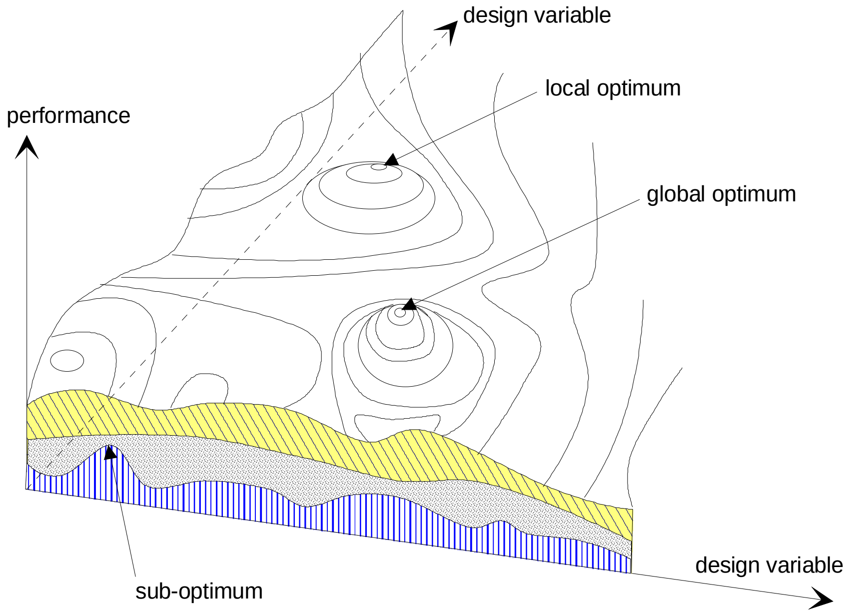


Figure 5-1. The performance landscape, adopted from (Mann 1992).

Thus, to sum up, a global optimization does not make sense because:

1. In our present state of the world, it is not possible to make a numerical model that incorporates all values of a design.
2. In practice, it is not possible to find the best of all possible solutions, because the solution space is endless.

Still, this does not necessarily mean that doing a sub-optimization is completely useless. One may want to study the detailed relationship between some important design parameters, and in this context, sub-optimization may offer useful insight. As long as one is aware of the limitations and the implications on the other criteria, it may give valuable information. An interesting approach to optimization of energy and costs (i.e. a sub-optimization) in building design has been presented by Kimmo Peippo at the Helsinki University of Technology (Peippo 1997). The low energy building design optimization problem has been formulated by the following two questions:

1. *Given the technical and economical characteristics of the building design options and their interactions as well as the project-specific boundary conditions and the economic environment: What is the optimum building design that minimizes the sum of the annual capital, operation and maintenance, and energy costs?*

2. *If, for any reason (to reduce CO_2-emissions, for instance) one wishes to use less energy than in the least cost design above, what is the system design that gives the desired reduced energy requirement at minimum cost. Or conversely, if extra funds are available for energy efficiency and solar measures, what is the system design that gives the highest energy savings at this given extra cost?*

A numerical optimization scheme is introduced that defines the optimal path so that, starting from the unconstrained least cost design, at each point on the path the system design will give the desired reduced auxiliary energy requirements at minimum achievable cost. Figure 5-2 shows an illustration of the result of such an optimization with insulation thickness and window area as variables.

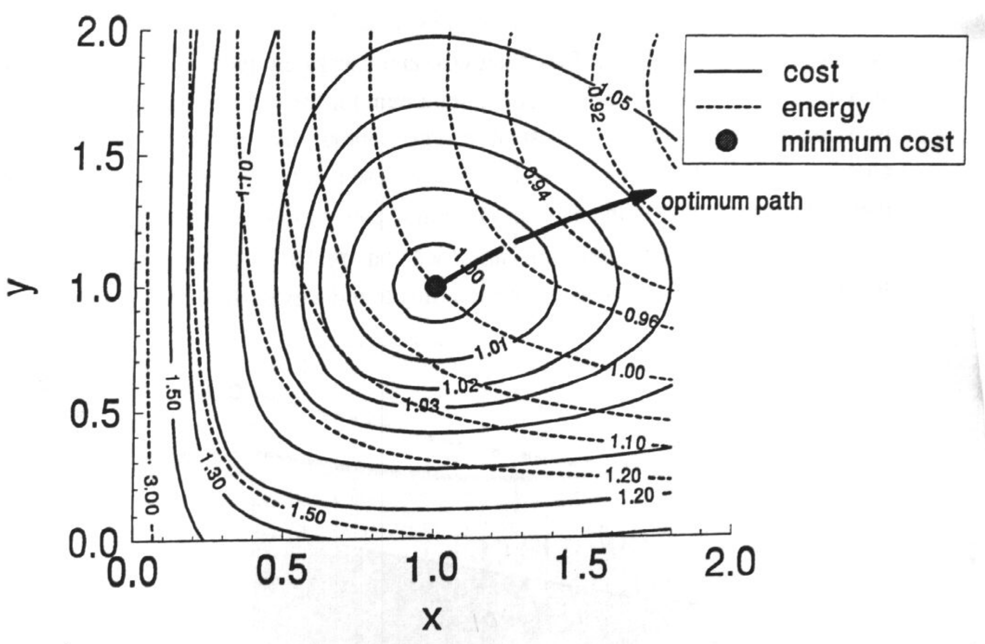


Figure 5-2. Illustration of an optimization problem in two dimensions and the optimal path for the constrained problem. X is the insulation thickness and Y is the window area of the building. All values are relative to the ones representing the minimum cost. From (Peippo 1997).

Peippo has used the procedure for a case example of finding the optimal allocation of façade area to different solar technologies, see Figure 5-3. The figure is interpreted as follows: The lower left hand corner represents a façade configuration optimized with respect to minimum life cycle costs. This façade consists of about 25% windows and 75% opaque wall with insulation. If the client would like a design that uses a little less energy and can accept a little higher cost, he should move towards the right in the figure. For example, he would like to reduce the energy consumption by 20%, the figure would tell him that he could choose a façade with advanced windows that covers 35% of the area, amorphous silicon PV cladding that covers 15% of the area, and opaque insulated wall on the remaining. This façade will cost about 10% more than the least cost design.

The example may appear somewhat theoretical because there are many other issues that will influence the choice of a facade cladding. The author also recognizes that this is in fact just a sub-optimization, and even makes mention of possible implications for daylight, comfort and aesthetics. Nevertheless, the example shows how a sub-optimization procedure may be used to provide insight into the relationship between a set of design parameters. This could help the general understanding of relationships between important design parameters. For specific problems in practical design work, however, such procedures are probably difficult to implement. Because every building project is unique and has its own special characteristics and objectives, it is not possible to have a general optimization procedure that will work for all cases. So the optimization would have to be constructed specifically for every project. Particularly in the early design phase, it is hard to justify putting a lot of time and effort into a detailed optimization of some performance characteristics. But also in the later design stages, care should be taken not to spend too much time on optimization procedures because they may attract the attention from other important aspect that can't be accounted for in a numerical way. This is further discussed in section 5.5.

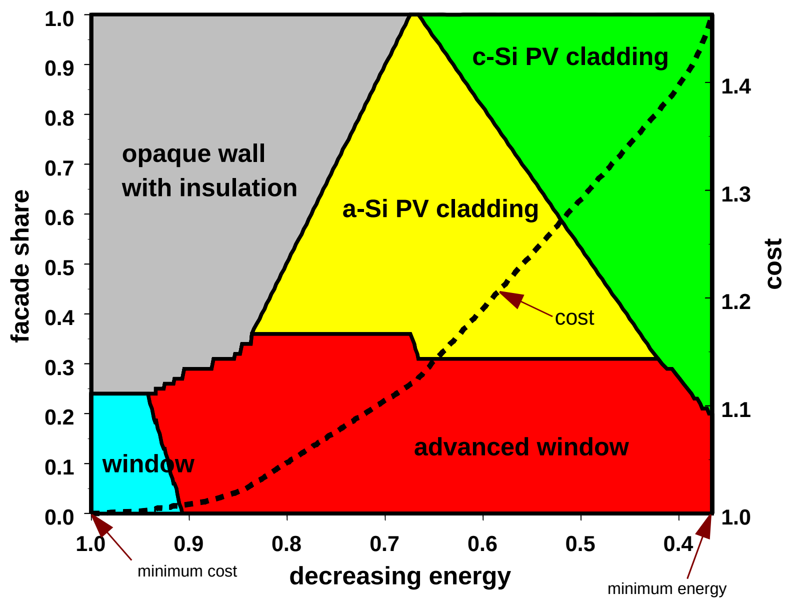


Figure 5-3. An example of optimal allocation of façade area to different solar technologies, staring from the least cost design on the left an moving towards decreasing energy requirements to the right. The horizontal axis shows the total building energy consumption compared to the economically minimum cost design, and the left vertical axis indicates the share of each technology on the south facing solar façade. From (Peippo 1997).

The concept of *satisficing* is often proposed in contrast to optimization. The term was first used by Herbert Simon in "The Sciences of the Artificial" (Simon 1969). Based on the fact that humans have a limited ability to foresee future consequences and obtain information about all alternatives, Simon assumed that people rely on a simplified model for describing an issue. He argued that decision-makers select a course of action that is good enough, and they have no intentions of achieving the absolute optimal course. When a decision-maker applies the satisficing strategy, he investigates if the requirements fall below or above some specified threshold. Simon argues (Simon 1964):

It is doubtful whether decisions are generally directed toward a goal. It is easier and clearer to view decisions as being concerned with discovering courses of action that satisfy a whole set of constraints. It is this set, and not any one of its members, that is most accurately viewed as the goal of the action.

Thus, this philosophy embraces the idea that it is not possible to find a global, optimal solution. But, does this mean that we should not even try to find the best possible solution that is within some limited solution space? It might be correct that many decision-makers more or less arbitrarily pick the first solution they find to be within the thresholds of acceptance. An alternative is chosen for implementation if it is judged to be “good enough” to satisfy the objectives and constraints. However, this seems to be a mediocre way of going about a design. Should we not strive towards achieving the best, even though we know that we cannot find the best of all possible? An attractive compromise seems to be that we should try to find the “best” alternative, in the opinion of the decision-makers, among the set of available and analyzed alternatives, but accepting the fact that this not necessarily is the best among all conceivable alternatives.

However, the point that Simon makes about *a set of* constraints, is interesting. This indicates that the alternatives have to be measured against a set of design criteria, and not one single one. This issue is further discussed in section 5.5.

5.3 Tools and Methods for Performance Prediction

In chapter 2, several tools for performance prediction of solar energy systems were described. There is a large number of tools available to the designers, including handbooks, simple calculation methods, and computer simulation models for quantitatively estimating the performance of solar buildings. Most of the tools concentrate on predicting the energy and economic performance of buildings and systems, some also give indications of comfort and environmental impacts. There is no tool that can predict the total performance of a building.

Thus, the designers are left with a wide range of different tools, ranging from simple guidelines to complicated computer simulation programs. Care should be taken not to employ more apparently accurate methods of measurement in design than the situation really deserves. There are two reasons why relatively simple models are usually quite sufficient in the early design phase. One is that there are inevitable unquantifiable aspects, hence it is impossible to deal with them on a purely quantitative basis There is therefore bound to be some fuzziness in the final recommendations no matter how precisely the quantitative aspects are handled. Hence, it is a waste of effort to seek out great precision.

The second reason is that reality is far more complicated than any model can be. In formulating a model one omits a great many factors that one judges to be relatively unimportant to the central issue of the analysis. It would be a waste of effort to try to make a highly elaborate model of a real situation when a sensible simplification will serve approximately as well. The marginal utility of increased accuracy in a model decreases with great speed once it begins to provide approximate results.

In addition, there is usually not enough detailed information available in the early design phase to support a detailed performance prediction. However, as the design evolves, and more details are being specified, more precise performance predictions may be carried out. This is reflected in the fact that the most common methods and tools for performance prediction in the early design phase are rules of thumb, intuition, gut feeling, experience, and simple calculation procedures. Detailed computer simulation tools are normally not used until later in the design.

5.4 Presentation of Results

Presentation of the results of the performance prediction is important because it is the basis for evaluating and choosing what alternatives to use. Several studies suggest that people's preferences are dictated by the presentation of a problem, (Tversky and Kahneman 1981), (Keller 1985), (Bell, Raiffa et al. 1988) describe the following illustrative case:

A group of subjects were asked to imagine that they had lung cancer and had to choose between two therapies on the basis of the following probabilistic assessments:

- Of 100 people having treatment A, 90 live through the treatment. A total of 70 people are alive by the end of the first year and a total of 38 people are alive by the end of five years.

- Of 100 people having treatment B, all live through the treatment. A total of 79 people are alive by the end of the first year and a total of 26 people are alive by the end of five years.

A second group of individuals was presented with the same choice, except that the data were presented in terms of mortality rates rather than survival rates (e.g., of 100 people having treatment A, 10 die during treatment, etc.).

There were vast differences in the responses depending on whether the data were presented in terms of survival rates or in terms of mortality. The proportion of subjects that preferred treatment B to A was 61% when the data were presented in terms of mortality and was only 37% when presented in terms of survivability.

Bazerman (Bazerman 1998) describes several examples where he shows that the choice of reference point influences the decision. In building design it is common to compare the performance of a potential solution with a mean performance, i.e. the average value for existing buildings. The location of the reference point can determine whether the decision will be positively or negatively framed, which may influence the decision in a similar way as in the example above.

Another aspect with presentation of results is that it needs to be clear to the people that are going to use it. The decision-makers are often clients or users that are unfamiliar with the language of the professionals. Also, the design professionals have to understand the results from the other fields in order to implement them into their own special area of expertise. Moreover, the results have to be put together in a way that makes the overview easy. At the same time, it should be possible to go behind the overall conclusions to see more details. Graphics are often useful to illustrate performances, e.g. pie charts, bar charts, and so on. This is a "language" that most people can understand. Graphics are also useful in showing relations and giving overview. The Decision Desktop in the BDA program that was described in chapter 2 (see Figure 2-18) is an example of an informative presentation of performance data for different design alternatives. The performances of the alternatives on the different criteria are displayed side-by-side to facilitate direct comparison of the alternatives.

5.5 Conclusions

There is no doubt that judgement is very important in building design, especially in the early design phases. There are many qualitative design considerations that cannot be included in a numerical calculation procedure. The qualitative issues are often very important to the decisions. In his book *The Reflective Practitioner* (Schön 1983), Donald Schön contrasts what he calls *technical rationality* to such judgements:

In the varied topography of professional practice, there is a high, hard ground where practitioners can make effective use of research-based theory and techniques, and there is a swampy lowland where situations are confusing "messes" incapable of technical solution. The difficulty is that the problems of the high ground, however great their technical interest, are often relatively unimportant to clients or to the larger society, while in the swamp are the problems of greatest human concern. Shall the practitioner stay on the high, hard ground where he can practice rigorously, as he understands rigor, but where he is constrained to deal with problems of relatively little social importance? Or shall he descend to the swamp where he can engage the most important and challenging problems if he is willing to forsake technical rigor?

The British architect and psychologist Bryan Lawson also criticizes the overemphasis on rigor at the expense of relevance. He calls it "the numerical measuring disease" (Lawson 1997):

Perhaps it is because design problems are often so intractable and nebulous that the temptation is so great to seek out measurable criteria of satisfactory performance. The difficulty for the designer here is to place value on such criteria and thus balance them against each other and factors that cannot be quantitatively measured. Regrettably numbers seem to confer respectability and importance on what might be quite trivial factors.

It is essential to keep the balance in performance prediction. This means that it may not be worthwhile to put a lot of efforts into fine-tuning and optimization of one aspect, if it is of little importance, or if other important issues are only treated superficially. A problem with advanced computer simulation tools is that people tend to be so fascinated and absorbed in the program that it is taken as *the* answer to the problem, and other issues may be neglected. In the 70's and 80's we saw a lot of examples of how the emphasis on energy savings led to neglect of indoor environment and occupant health. We may also find examples where tedious calculations of the overheating probability in offices have been carried out to find that there is no need for shading of windows - but glare problems have been forgotten.

Schön (1983) also warns against putting too much confidence in technical precision when in reality there are large uncertainties in the predictions:

Many practitioners, locked into a view of themselves as technical experts, find nothing in the world of practice to occasion reflection. They have become too skillful at techniques of selective inattention, junk categories, and situational control techniques which they use to preserve the constancy of their knowledge-in-practice. For them, uncertainty is a threat; its admission a sign of weakness. Others, more inclined *toward reflection-in-action, nevertheless feel profoundly uneasy because they cannot say what they know how to do, cannot justify its quality or rigor.*

In the early building design phase, there is definitely a lot of uncertainty, and it is often ignored. Handling of uncertainty is further described in chapter 6.

In section 5.2, it was concluded that a global optimization procedure is not useful for building design, or at least it would be too ambitious for building design at its current state. On the other hand, satisficing was deemed to be too little ambitious because it does not encourage a search for improvements. Somewhere in between these two extremes lies the pursuit of a "best" solution with respect to a set of criteria and constraints, given limited time and resources.

Although a global optimization is not feasible, a sub-optimization may be useful. A sub-optimization permits using greater detail in the analysis and may help understand important interactions. It allows us to study a part of a problem at a time, thus making the performance prediction simpler. Also, a study will, to some extent, always be a sub-optimization because there will always be some limitations. On the other hand, a sub-optimization leaves out important considerations. How then, can we sub-optimize properly? The answer is that we must make sure that the action that improves one part also improves the whole. This may be achieved by using a hierarchical structure of criteria and keeping the criteria at the lower-level problem consistent with the criteria at the higher levels.

In chapter 3 (Problem Formulation) it was argued that a hierarchical structure of design criteria would be useful for information management and a suitable basis for evaluating alternative solutions. Such a structure may also be a useful basis for performance prediction. If the hierarchy is structured according to the objectives of the stakeholders, it will help promote a balanced performance prediction. The hierarchy allows for dividing the problem into separate units while keeping track of the interactions. If the problem is carefully separated into parts at places where the interactions between parts are weakest, improvement in a subsystem will produce the appropriate improvement in the system as a whole.

Finally, presentation of the results of the performance prediction is important. Several studies show that choice is strongly influenced by the framing of the outcome. When evaluating design solutions, the conclusion may depend on the choice of reference for the different criteria. A consistent set of reference points for the criteria should therefore be used, and different viewpoints should be tried out. In this way the design team could really live up to the ideal of being *reflective practitioners*.

Everything is relative.

6 Performance Evaluation

6.1 Introduction

This chapter deals with the central issue of this thesis; the task of performance evaluation. The objective of performance evaluation is to test if potential solutions meet the design objectives, in order to select the most promising design. It is presumed that a set of potentially feasible design solutions has been generated (or can be imagined). The design solutions are described by a set of attributes. An attribute is a characteristic of an option being evaluated that is measurable against some objective or subjective yardstick. It is also assumed that some design criteria (objectives) have been prescribed. If more than one alternative satisfy all the criteria to some extent, it is necessary to do some sort of evaluation to determine how well the different alternatives satisfy the criteria. Also, it may be needed to identify what criteria are more important, i.e. to determine the weights between the criteria.

The following section of this chapter (6.2) contains a survey of evaluation models used within the building industry and within the field of environmental planning.

Section 6.3 includes a survey of Multi-Criteria Decision-Making (MCDM) methods. The purpose of MCDM methods is to identify a preferred alternative from a set of alternative solutions that are characterized by multiple, usually conflicting attributes. Thus, they seem to fit well into the scope of this thesis. MCDM methods have found applications in many fields, including policy analysis, management science, psychology, and environmental planning. However, there are very few applications to be found within the building industry, although recently some efforts have been initiated. The most central of the MCDM methods are described and their appropriateness for the framework of the thesis is discussed.

Section 6.4 includes a discussion of how to include and treat uncertainty, risk, and fuzziness in the evaluation of design options.

Section 6.5 is a conclusion of the three previous sections, where the most promising features of the models described in sections 6.2, 6.3 and 6.4 are pointed out. Here, a multi-criteria evaluation model for use in solar building design is beginning to emerge.

Section 6.6 takes a closer look at measurement theories, discusses different models, and identifies what procedures are most suitable for use in building design.

In section 6.7, techniques for weighting of design criteria are discussed.

Section 6.8 is the conclusion of chapter 6. It summarizes the findings of the previous sections, and identifies promising aspects to include in a multi-criteria evaluation model for building design.

6.2 A Survey of Evaluation Methods used in the Building Industry and Environmental Analysis

This section includes a survey of evaluation models used within the building industry and the field of environmental analysis. Within the building industry, there is no practice for multi-criteria evaluations. Although a range of different design objectives is implicitly present in building design, it is not common to use any kind of model in order to systemize them. Most often, some sort of cost estimate is carried out which in turn is compared to the quality or value of the building design in some informal way. The models from environmental analysis are interesting because they seek to make the comparison of cost and benefits more explicit.

Cost-Benefit Analysis (CBA)

Cost-benefit analysis (or benefit-cost analysis) is the principal analytical framework used to evaluate public expenditure decisions. A CBA consist of the following steps (Mishan 1971; Pearce 1971; Dasgupta and Pearce 1972; Pearce and Nash 1989; Bojö, Mäler et al. 1990):

- Identification of costs and benefits
- Quantification and evaluation of costs and benefits in terms of a common monetary unit
- Choice of a social rate of discount
- Choice of a time horizon
- Construction of a one-dimensional indicator bringing together all the benefits and costs (many authors suggest the use of the net present value)

Having measured all benefits and costs in money terms, the following maximization rule is applied:

$$\max \sum_{t}^{T} \frac{B_t - C_t}{(1+r)^t}$$

where B_t and C_t are benefits and costs in time period t, r is the discount rate and T is the time horizon. Obviously, if B_t and C_t are in different units, no such decision rule can be used. In order to be consistent with the objective of maximizing social welfare, it is necessary that the prices attached to the benefits and costs reflect society's valuation of the final goods and resources involved. For this, different valuation approaches have been proposed, for example the use of "conventional markets", "implicit markets", and "artificial markets", see (Bojö, Mäler et al. 1990) for a further description.

CBA has been criticized on many points; some of the main critics include:

- It hides important value judgments.
- It assumes that it is possible to choose objectively the market place in which to value an effect.
- It appears to be objective, but is in fact heavily laden with value judgements.
- It assumes that money is a common numeraire of preference and that it automatically accomplishes interpersonal comparisons.
- Time preferences are assumed to correspond to simple discounting, whether or not the effects are monetary.

One of the main problems with using CBA in building design is that it is almost impossible, or at least very time consuming to convert all aspects into terms of money. The valuation techniques used for converting qualities into money terms are very complex.

Another problem is that the valuation used in CBA does not necessarily match the needs of the stakeholders in a building project.

The Scorecard Model

Massey (Massey 1988) describes a scorecard technique developed by Goeller in analyzing effects of transportation alternatives (Chesler and Goeller 1973). An example of such a scorecard is shown in Figure 6-1 (adapted to a building evaluation framework). Each of the impacts are presented in its natural units, rather that being converted into a single measure of worth, such as monetary units. The comparative rankings of the alternatives for a single impact are indicated by color coding; green indicates an alternative with best outcome for this impact, yellow indicates intermediate outcome, and red indicate the worst outcome. Thus, a scorecard for a set of alternatives is a table showing both the rank-coding and numeric outcomes for the different impacts.

	Functionality	Energy cons.	Comfort	Aesthetics
Alternative 1	good	100	very g	bad
lternative 2	mean	155	good	good
lternative 3	good	95	mean	mean
lternative 4	mean	53	bad	good
lternative 5	good	76	good	very g

Figure 6-1. Example of a scorecard, adapted from (Massey 1988).

Massey (1988) suggest that the scorecard lends itself to presenting results of sensitivity analysis through use of overlays to show the changes in rankings that result from different sets of assumptions. In this way it can help to find situations where the rankings of alternatives are insensitive to certain assumptions whether or not the absolute levels of costs or benefits are sensitive to them. This is largely because of the advantages of color coding, which can convey an overall impression of how rankings change more readily than can other rank-coding schemes. Massey (1988) summarizes the advantage of the model as follows:

It provides factual information about the costs, benefits, and disbenefits of complex choices without imposing external views about the relative importance of the attributes. The decisionmakers can then add to this information their feelings for human values and the values of the society they represent, the intangibles that underlie all human decision-making.

The main problem with this model is that it may be quite difficult to identify the most preferred alternative. Even if the criteria all have the same weight, the scorecard may be hard to interpret. For example, is alternative 2 which has two "good" scores, one "bad" score, and one "mean" score, better than alternative 3 which has one "good" score and three "mean" scores? The method resembles the simple ordinal ranking method described in section 6.3, and hence, its usage is similar.

Peňa's Quality Quotient Model

William Peña (Pena 1987) describes an evaluation technique based on quality measurements that they have used in his architectural firm CRSS in South Carolina. For each of the main issues or "forces", Function, Form, Economy and Time, the magnitude of the "force" is determined empirically with the following measurement scale:

Complete failure	1
Critically bad	2
Far below acceptable	3
Poor	4
Acceptable	5
Good	6
Very good	7
Excellent	8
Superior	9
Perfect	10

To aid in determining accurate values for each of the four "forces", questions sets have been developed, see Figure 6-2. By using the same value measurement scale to respond to individual questions covering each of the four categories, the final values can be determined more easily. The result is presented in quadrilateral diagrams as shown in Figure 6-3, or as a single score, called the Quality Quotient, which is equal to the area of the quadrilateral. Ten points for each area of concern gives a Quality Quotient of 200; the perfect building. A quadrilateral with five points for each "force" is the absolute minimum acceptable.

Function

A. To what extent have organizational concepts been uncovered?
B. How well documented are the client's functional relationships and goals?
C. How much discrimination has been used to distinguish between important form givers and details?
D. How realistic are the space requirements based on statistical projections, client needs and building efficiency?
E. How well identified are the user's characteristics and needs?

Economy

K. To what extent are the client's economic goals and budget limitations defined?
L. How well documented is the local cost data considering methods of financing, planning and construction?
M. How well documented are the factors of climate and activities considering maintenance and operation costs?
N. How comprehensive and realistic is the cost estimate analysis?
O. To what extent have economy concepts been uncovered?

Form

F. How clearly expressed are the client's form goals?
G. To what degree was rapport established with the client and the design team on quality and the cost per square foot?
H. How thoroughly is the site and climate data analyzed and documented?
I. To what extent has the surrounding neighborhood been analyzed for its social, historical and aesthetic implications?
J. To what extent have psychosocial environment concepts been uncovered?

Time

P. To what extent does the program consider historical preservation and cultural values?
Q. To what degree have major activities been identified as static or dynamic?
R. To what extent does the program anticipate the effects of change and growth?
S. How well has the time factor been utilized to escalate costs and determine phasing?
T. How realistic is the time schedule for the total project delivery?

Figure 6-2. Question sets for evaluating performance during programming, (Pena 1987).

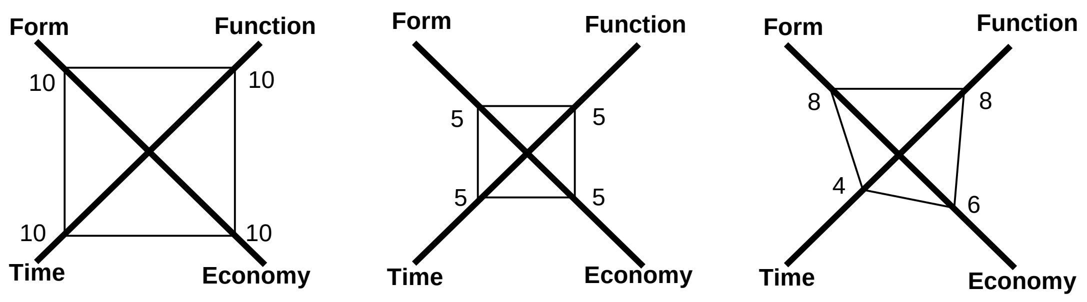


Figure 6-3. Scoring Diagrams for a "Perfect Building", a "Barely Passing Building", and a "Normal Building", adapted from (Pena 1987).

This model shows a way of performing an evaluation that starts out with qualitative measures and converts them into numerical values. Peña argues strongly for quantification of qualities, because, as he states, "*a symbol such as a score is a good way to immediately perceive a situation*", (Pena 1987). Furthermore, he claims that quantification of quality is important because everyone, particularly users, judges our buildings. However, he does not devise a very specific way of transforming the qualities into the numerical scale; the question set that he supplies as an evaluation aid, is very loose.

The scoring diagrams that are used to present the results of the evaluation are very illustrative. They give a picture of the overall score of the design, while at the same time showing the scores on the individual criteria (“forces”). Note that no weighting of the criteria is included.

The Weighted Evaluation Technique of Dell’Isola and Kirk

Dell’Isola and Kirk (Kirk and Dell'Isola 1995) describe a weighted evaluation technique that they have developed for use in building design projects. The method is illustrated for a case of choosing between different exterior wall constructions. The various criteria are weighted numerically according to the importance that is attached to them. The wall constructions are scored according to the degree to which they meet the criteria. Finally, an overall score is calculated for each alternative. The weighted evaluation procedure works in the following way (see Figure 6-4):

Each of the criteria that the wall must satisfy are listed in the criteria scoring matrix in the top half of the form (A, B, C, etc.). Then, the criteria are systematically compared with each other in terms of direction and strength of performance. For example, “Durability” (criterion F) is given minor preference over “Operational Effectiveness” (criterion e) and so is assigned a score of 2 (F-2) in the appropriate cell of the criteria scoring matrix. “Image/Aesthetics” (A) and “Color Rendition” (B) are ranked equally, giving the entry A/B. The process is repeated until all the criteria have been compared with one another.

The raw scores for each criterion are found by adding up the numbers in each cell where a preference for a particular criterion has been registered. For example, to obtain the raw score for criterion D, all the cell in the two diagonals originating from D are examined. The upward sloping diagonal contains D-2, D-2, and D-3, and the downward sloping diagonal D/E, D/F, and D-4. This gives a total score for G of 2+2+3+1+1+4=13. This is done for every criterion to generate the raw score line. These raw scores can now be used directly in the next stage of the exercise. However, for convenience, they are converted into a set of weights on a scale from 1 to 10.

The second stage requires each wall construction to be scored (on a range of 1 to 5) according to the degree to which it satisfies each of the criteria. These scores are inserted in the top box of each cell of the analysis matrix, beneath the criteria matrix. Thus, for example, construction type 1 is rated as “good” (score of 3) on criteria C and G. The scores are then multiplied by the weights to give the entries in the lower box of each cell of the analysis matrix. For example, construction type 1 is given a score of 20 (2x10) for criterion F.

The overall score of each wall construction type is computed simply by adding the scores in the lower boxes across the whole row of criteria. In summary, what the weighted evaluation of Figure 6-4 does is firstly to identify the relative importance of the various criteria. Secondly, it shows the extent to which the various finishes satisfy these criteria, both individually and in aggregate.

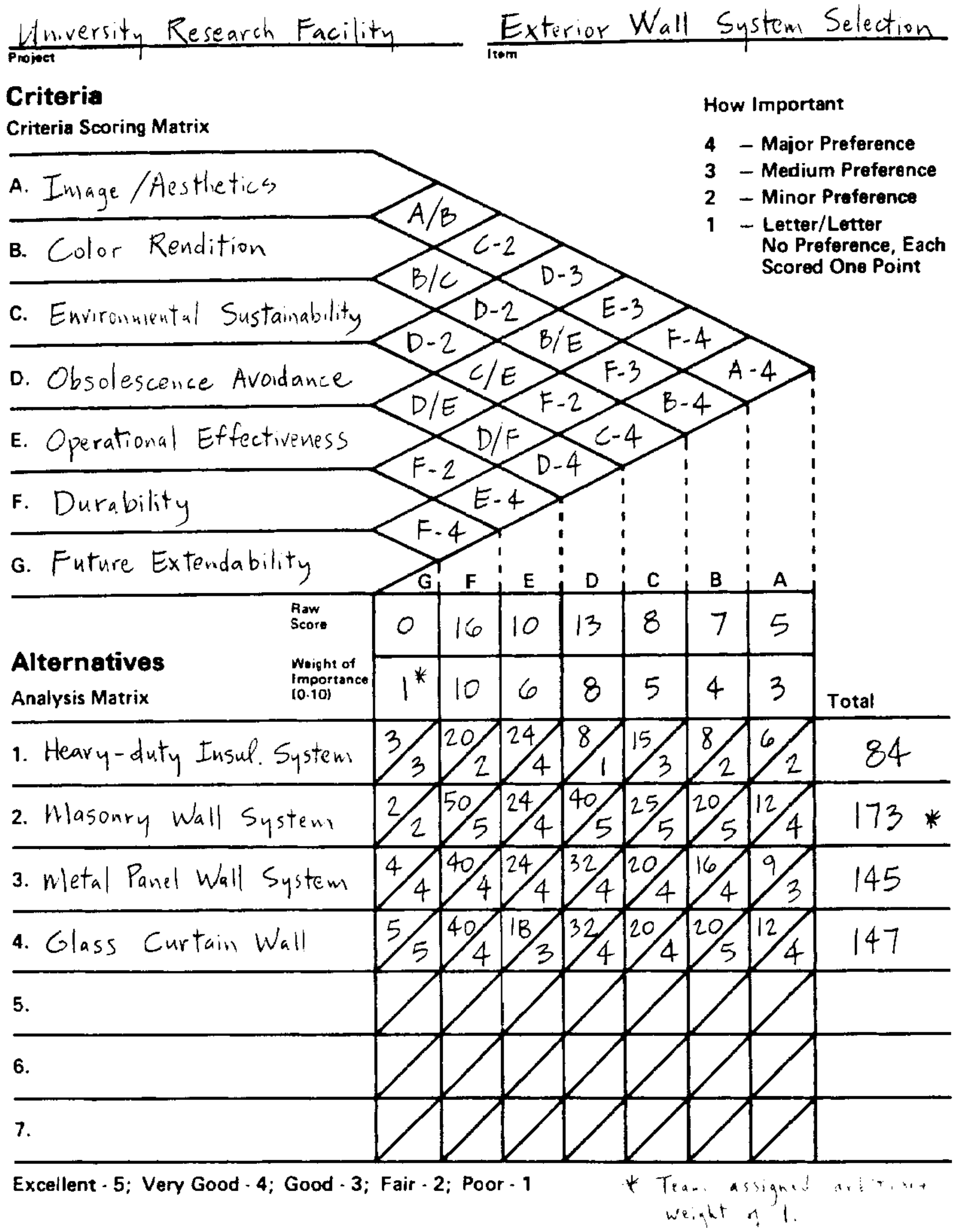


Figure 6-4. Example of use of the weighted evaluation Model by Dell'Isola and Kirk, (Kirk and Dell'Isola 1995).

This model is interesting in that it presents the entire weighting of the criteria, the scoring of the alternatives, and the aggregation of the weights and scores into an overall measure of goodness for each alternative, in one diagram. This gives a good overview of the evaluation procedure. The pairwise comparisons of criteria may obscure the overview, but putting them into a comprehensive form like this, partly makes up for this drawback. However, consistency checking is left to the user. Another problem with the pairwise comparisons may be that it becomes a tedious process when there are many criteria. An additional problem may arise if the number of alternatives and criteria increases; - the matrix may be too big to fit into a normal sheet. These issues are further described in section 6.3.

The Synthesis Model of Kirk and Spreckelmeyer

In their book “Enhancing Value in Design Decisions” (Kirk and Spreckelmeyer 1993), the American architects Stephen J. Kirk and Kent F. Spreckelmeyer propose a model for comparing design alternatives. In this model, the performances of individual components are measured against the design goals, in a similar manner as the previous model. The model may be used during different stages of the design process.

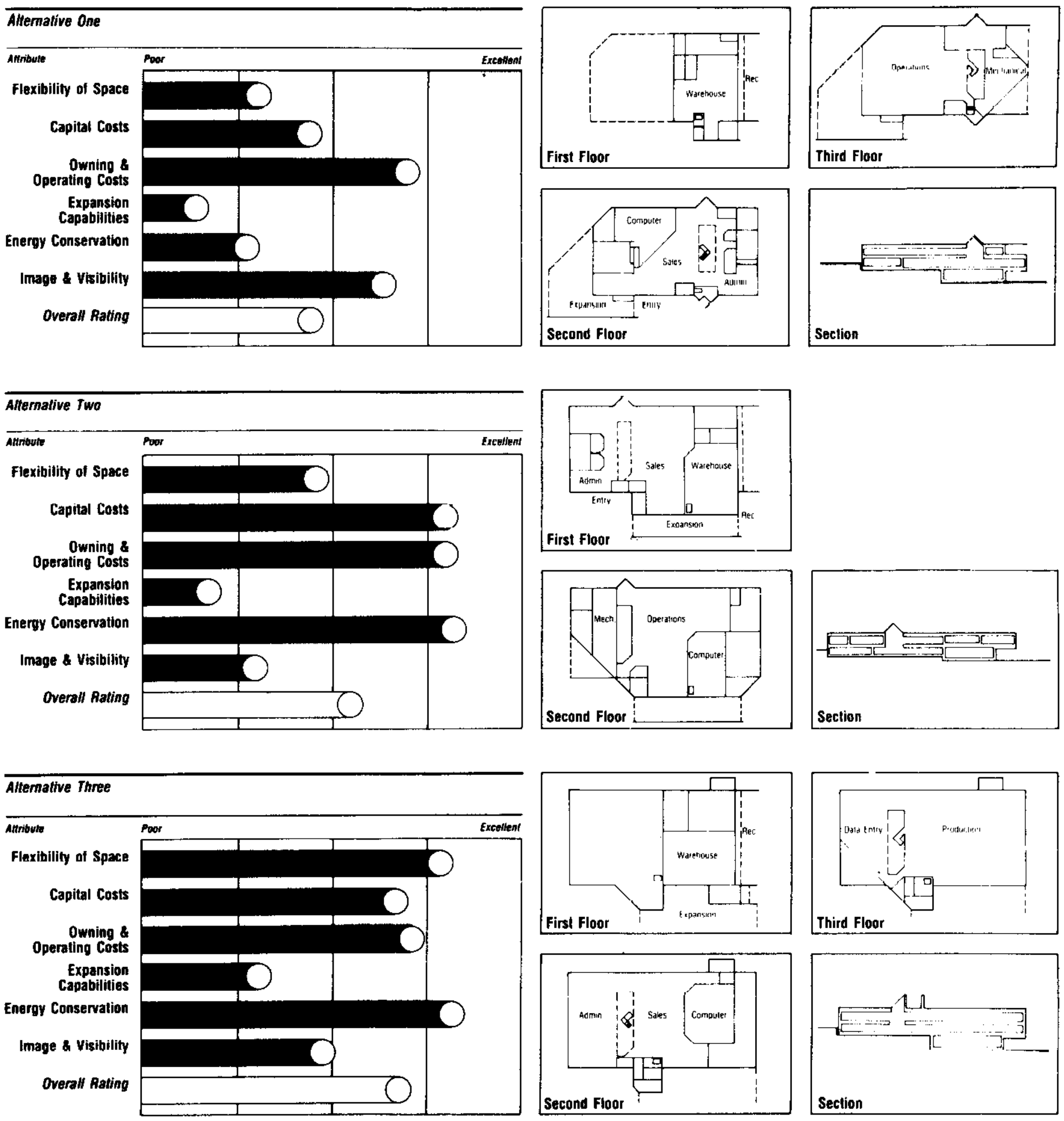


Figure 6-5. Building layout evaluation and synthesis, from (Kirk and Spreckelmeyer 1993).

Figure 6-5 shows an example of the model used during the feasibility study. Here different building layouts are evaluated. The layouts are measured with respect to the six main design goals: flexibility of space, capital costs, owning and operating costs, expansion capabilities, energy conservation, and image & visibility. The performance scale ranges from “poor” to “excellent”. The bottom bar shows the overall ranking which is a synthesis of the rankings on the individual criteria. Figure 6-6 shows and example of the model used in a later design phase. Here, different exterior closures are studied. In addition to showing performance scores, the model in this case also shows the weighting of the criteria and the aggregated weights and scores for all the alternatives. A simple additive weighting model (described in section 6.3) is used to aggregate scores and weights.

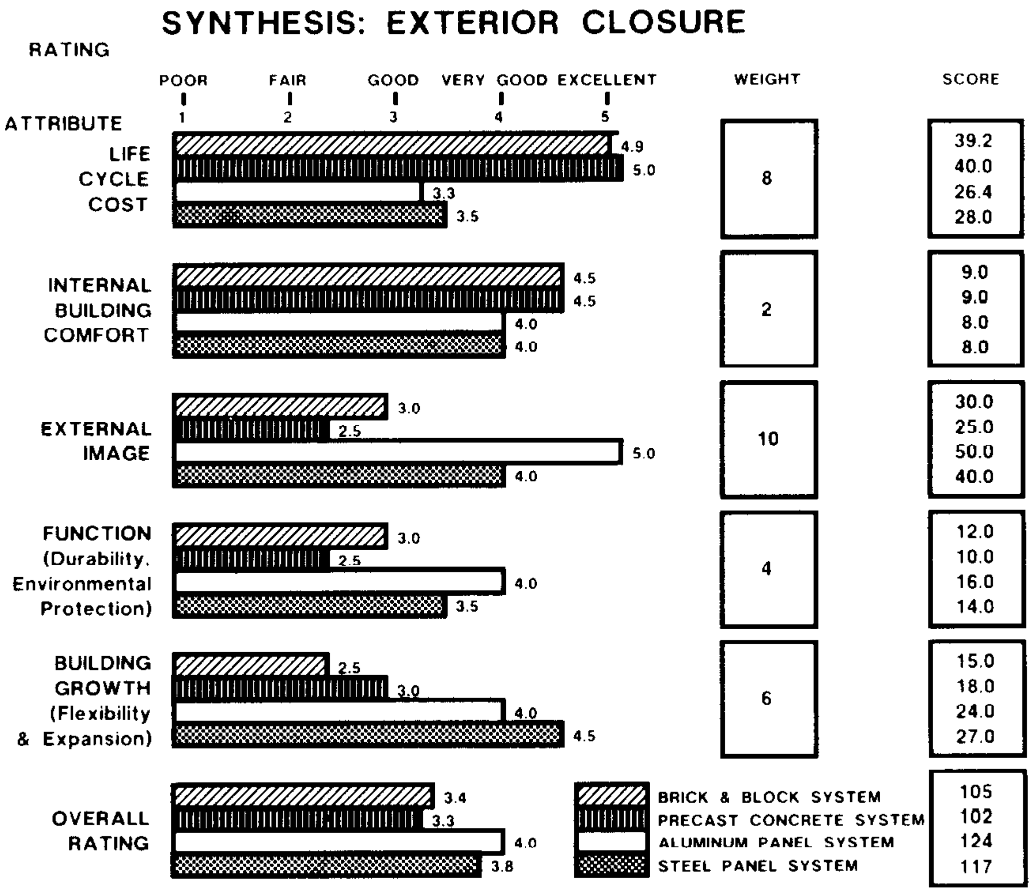


Figure 6-6. Evaluation of exterior closures, from (Kirk and Spreckelmeyer 1993).

The graphical display of this model gives a good overview of the performance evaluation as a whole, while showing the individual performance measures that have been carried out. However, there is a limit to the amount of detail that can be shown.

An Expert Based Qualitative System Used in LCA

In a basically qualitative Life Cycle Analysis (LCA), Christiansen et al. (Christiansen, Grove et al. 1990) used two different matrixes for the evaluation. The first matrix was used for a specific assessment and the second for a comparative assessment.

In the specific assessment matrix, six steps of the life cycle were combined with six consequence elements, as shown in Table 6-1. Key impact areas are noted using a 4-level scale:

Potential for severe impact: ---
Potential for impact: -
Potentially no impact: *0*
Lack of knowledge: *?*

In the comparative assessment, an alternative was compared to the base alternative in a similar matrix. The same steps in the life cycle were included, however, the exposure and effect parts of the work and external environment were combined. A scale going from "potentially much less impact than the base alternative" (+++) to "potentially much greater impact than the base alternative" (---) was used. The valuation system was completely expert-based and no criteria were given for the representation of different impacts in neither of the matrixes.

Table 6-1. Example of a specific assessment matrix used in the study, (Christiansen, Grove et al. 1990).

	Life Cycle Stage					
Consequence	Production of raw materials	Production of semi-products	Manufacturing of final products	Use	Recovery	Waste Management
Consumption of resources	**---**	**---**	**0**	**-**	**0**	**0**
Accidents	**--**	**--**	**-**	**?**	**-**	**-**
Work environment – exposure	**-**	**--**	**-**	**---**	**-**	**-**
Work environment – effect	**--**	**---**	**-**	**-**	**-**	**--**
External environment – exposure	**--**	**?**	**-**	**-**	**0**	**-**
External environment – effect	**---**	**-**	**-**	**--**	**-**	**0**

The separation of impacts of different life cycle stages may be interesting also for use in building design. Designers tend to focus only on the construction phase, and forget to include the consequences prior and following the construction that might be of significant importance.

The use of +/- signs to indicate scores gives a very crude indication of the relative performances. This may be useful to screen out inferior alternatives, which is valuable in the early design stage. However, it is not suitable for aggregation of the different scores in order to get a measure of the total value of an alternative action. Dissimilar weights of the different criteria are also hard to include in such a model. This issue is further discussed in later sections of this chapter.

An Expert-Based Quantitative Method Used in LCA

In a Dutch study (Annema 1992), an expert based quantitative system was used for positioning different options on a diagram with the environmental yield on one axis and the economic impact on the other axis. The scores for the different impact categories were normalized by relating the scores to the total score of that category in the Netherlands, resulting in an environmental profile. The final step was to apply weighting factors to the different impact categories. This was done in a Delphi-like process (the Delphi process is described in chapter 4).

In the weighting process, members of a steering group representing industry, government, environmental groups and some independent persons from universities and scientific institutes were involved. The process was a four-step approach. The aim of the first step was to gain a common understanding of the importance of the impact categories and of facts that were included in the environmental and economic profiles. A basis for the discussion was a framework in which different aspects of the different categories were defined. This could involve a discussion about whether the impact affects humans or ecosystems or both, the degree of scientific uncertainty, the degree of reversibility of the impact, the scale of the impact, the timing of the impact, and other issues.

The second step of the weighting process was a first assessment of the weighting factors. This step was done by each member confidentially. In the third step, the resulting positioning on the diagram was presented to the members who continued their discussion to improve the common understanding of the problems. The fourth step was a second assessment. The process was then repeated until all options had been positioned on the diagram.

The “EPS-system”

The EPS (Environmental Priority Strategies in product design) system is developed by the Swedish Environmental Research Institute (IVL) and described by (Steen and Ryding 1992). It is a system for assessing environmental impacts in terms of ecological and health consequences. Five “safe guard objects” are valued, these are: biodiversity, production, human health, resources, and aesthetic values. These objects are valued according to the willingness to pay to restore them to their normal status. Emissions, use of resources and the human activities connected to a product are then valued according to their estimated contribution to the changes in the safe guard objects, and added. The resulting environmental effect of an action is expressed in ELU (Environmental Load Unit). One ELU corresponds approximately to one EURO. The EPS system thus results in an economic valuation of the environmental impacts. In this respect it is similar to the Cost Benefit Method described earlier.

"Green Building" Assessment Tools

Recently, a number of "green building" assessment tools for evaluating the environmental performance of buildings have been developed. Virtually every developed country now has their own program, for example the U.K. *BREEAM* (Prior 1993), the Canadian *BEPAC* (Cole, Rousseau et al. 1993), The Dutch *Eco-Quantum* (Mak, Anink et al. 1996), the French *ESCALE* (Chatagnon, Nibel et al. 1998), the U.S. *LEED* (U.S.G.B.C 1999), and the Norwegian *Økoprofil* (GRIP 1996). In essence, these programs are devoted mainly to evaluating the environmental performance of existing buildings by some sort of rating system. Through an international collaboration, the Green Building Challence'98, a second-generation environmental assessment tool has been developed - *GBTool* (Larsson and Cole 1998). This tool incorporates a wider range of criteria, i.e. other criteria than environmental loadings, such as functionality and management issues. GBTool is also developed with the future use as a design tool in mind. Hence, this program is the one that is most closely related to the work in this thesis. Therefore, a closer look at this program may be useful.

The GBTool was developed within the Green Building Challence'98 project, a 2 year international project with 17 countries participating (Larsson and Cole 1998). GBTool is a framework and software tool for assessing the energy and environmental performance of buildings. Main design goals were:

- to focus on relativistic assessments, by relating assessments to benchmarks that are based on applicable regulations or industry norms in each of the participating regions

- to establish a structure that can be used at various levels of detail, from broad-brush assessments to detailed ones, and that can also subsequently be expanded to a design guideline system

- to establish a scoring system that accepts both hard and soft data in similar format.

GBTool is structured hierarchically in four levels, with the higher levels logically derived from the weighted aggregation of the lower ones:

1. Performance Areas
2. Performance Categories
3. Performance Criteria
4. Performance Sub-Criteria

The nesting principle of four levels is a critical feature of the framework in that it enables a building performance to be described at successively detailed levels. A scoring scale ranging from –2 to +5 is used for assessing all criteria and sub-criteria. The performance level required to achieve a certain score is based on the 0 level being the reference or industry norm level; a –2 is significantly inferior and a +5 is set so that it is extremely difficult to reach. Most of the scores for the various criteria are presented on a scale that gives more points for a given increment in performance as the overall performance level increases. The rationale for this being that it becomes increasingly more difficult to attain performance improvements. Figure 6-7 gives an example of such a performance scale. Performance scales are further discussed in section 6.6.

Score	Default Performance
-2	The annual operating energy per m2 of gross floor area of the case-study building is 45% GREATER than that of the Reference Building.
-1	The annual operating energy per m2 of gross floor area of the case-study building is 20% GREATER than that of the Reference Building.
0	The annual operating energy per m2 of gross floor area of the case-study building is EQUIVALENT to the Reference Building.
1	The annual operating energy per m2 of gross floor area of the case-study building is 25% LESS than that of the Reference Building.
2	The annual operating energy per m2 of gross floor area of the case-study building is 40% LESS than that of the Reference Building.
3	The annual operating energy per m2 of gross floor area of the case-study building is 55% LESS than that of the Reference Building.
4	The annual operating energy per m2 of gross floor area of the case-study building is 65% LESS than that of the Reference Building.
5	The annual operating energy per m2 of gross floor area of the case-study building is 70% LESS than that of the Reference Building.

Figure 6-7. Performance scale for the criterion "Operating energy consumption" in the GBTool, (Cole and Larsson 1998).

Within the GBC documentation a series of criteria is offered as a basis for developing appropriate weightings such as: Is the effect upon the environment irreversible? Is the effect upon the environment long lasting? What are the numbers of people effected by the issue covered by the sub-criterion or criterion? Does the practice in question have momentum that will require an extraordinary effort to counter? However, no clearly defined methodology was proposed for their application. The weights and scores for the different criteria are aggregated using a simple additive weighting method (see section 6.3).

Several criticisms and observations were raised about the GBTool process (Cole and Larsson 1998), summarized as follows:

- Users felt that the tool required excessive time and effort to gather the data necessary to make the assessments. The perception that after a massive effort of data collection and input, the final performance scoring can be skewed by a subjective judgement.

- The level of detail must be the same for both the quantitative and qualitative information. If this is not possible, then it would be better to exclude the qualitative parts from the assessment based on a scoring system, and simply rely on a descriptive evaluation.

- The approach mixes the importance of a criterion with the difficulty of achieving it. In customizing the weighting system, "degree of difficulty" should not be a factor. Instead, the difficulty of achieving a specific level of importance should be reflected in the benchmarks; if a sub-criterion is particularly difficult, the zero value should be set at a level that is easier to achieve.

- GBTool does not compare or assess groups of issues between criteria, nor does it assign importance to synergies. Given that green buildings are recognized as much by the integration of systems and strategies, this is a serious limitation, particularly if used as a design tool.

It was an overall consensus that GBTool had to be streamlined to distinguish between those issues that are important and those that are merely interesting, and omitting the latter. The experiences of the GBC project are very useful also for the framework of this thesis.

Discussion

It is possible to identify 3 different approaches to performance evaluation:

1. Side-by-side comparison of alternatives with respect to performance criteria. Each attribute is measured on it's own separate scale, see Table 6-2. This means that the selection of the preferred alternative is made implicit, i.e. without any formal approach for comparison of attributes or weighting of criteria. The scorecard model is an example of this approach.

2. All attributes are measured on the same scale, but weighting of criteria is done implicit. The scale may be numerical or non-numerical, see Table 6-3 and Table 6-4. The expert-based LCA methods described above are examples of this approach.

3. An overall measure of the relative "goodness" of each of the alternatives is calculated by one of the following approaches:
   (a) Converting all aspects into one criterion (e.g. money), like in the CBA.
   (b) All attributes are measured on the same scale, the criteria are weighted, and the scores and weights for each alternative are aggregated into an overall measure of goodness. Most of the "green building" assessment tools use this approach. Also the method proposed by Dell'Isola and Kirk and the method by Peña (assuming equal weights) are based on this approach.

Table 6-2. Side-by-side comparison of alternative solutions using individual performance indicators.

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Alternative 1	50 kWh	100 g	good	$ 4000	nice
Alternative 2	20 kWh	70 g	average	$ 3500	ugly
Alternative 3	10 kWh	40 g	very good	$ 3000	normal
Alternative 4	15 kWh	50 g	bad	$ 2800	very nice

Table 6-3. Side-by-side comparison of alternative solutions using a common numerical scale (0-10) for performance measurement.

	Criterion 1	Criterion 2	Criterion 3	Criterion4	Criterion 5
Alternative 1	4	2	7	3	7
Alternative 2	5	4	5	4	1
Alternative 3	7	7	9	5	5
Alternative 4	6	5	2	6	9

Table 6-4. Side-by-side comparison of alternative solutions using a common non-numerical scale for performance measurement.

	Criterion 1	Criterion 2	Criterion 3	Criterion4	Criterion 5
Alternative 1	-	-	++	--	++
Alternative 2	0	-	0	-	---
Alternative 3	++	++	+++	0	0
Alternative 4	+	0	--	+	+++

Evaluation involves judgments about how well the potential design solutions are likely to fulfill the performance criteria. This implies assignments of "goodness" or "appropriateness" to the predicted performances. Since "good" and "bad" only make sense when there is at least two of a kind, a comparison of the different alternatives must be carried out. Direct side-by-side comparison of the alternative solutions with respect to the performance criteria can be effectively achieved by using a matrix structure such as the one in Table 6-1 (type 1 approach). Some sorts of performance indicators are used in order to show how well the different alternatives perform with respect to the different criteria. Different performance indicators for the different criteria are used. For example, energy performance may be measured in annual kWh electricity and fuel consumption per square meter, environmental loadings in annual emissions of kg CO_2, SO_2 and NO_x per square meter, etc.

To get an explicit and overall measure of how well the alternatives score with respect to all criteria, a common set of performance indicators is required (type 2 approach). This can be achieved by establishing a common *reference scale* for each of the criteria. For example, a numerical scale from 0 to 10 may be used, with 0 designating the minimum acceptable or practically realizable value and 10 designating the best possible value. Several of the models use a reference value for each attribute as a basis for the measurement, i.e. determines the deviation from this.

In CBA (approach 3a), an overall measure of goodness is calculated by converting all aspects into one criterion (money). This gives a well-defined mathematical model that can be used to select the best alternative. However, this approach involves valuation techniques that may be very complex and time consuming. Criteria weights are buried into the valuation model. In the other approach that involves the measurement of multiple attributes (3b), the weights for the different criteria are determined explicitly. The weights and the scores are then aggregated to produce an overall measure of goodness for each alternative. Thus, the introduction of weights is a way of modeling the relationship between the different criteria. This is in essence quite the same as merging all criteria into a single criterion. Therefore, (3a) and (3b) are very much related techniques. The difference is that in 3b the common scale does not have to be money, and that the weights are explicitly defined instead of being buried into the valuation. In my view, model (3b) is more transparent and mathematically less complicated, which makes it the most interesting for building design. Unfortunately, it still does not make the evaluation an easy task. The details of the model will be further discussed in sections 6.3, 6.6 and 6.7.

In the models included in the above survey, the most used aggregation model is a simple additive weighting method, where the attributes are measured on a common scale, multiplied by their respective weights, and added into an overall measure of goodness (3b). However, I did not find any information about the background for choosing this method or the prerequisites for using it, in any of the approaches surveyed. When it comes to measuring attributes and creating scales, the methods give very little guidance or discussion of how to do this. This is surprising, since the measurement of attributes may be crucial for the final outcome of the evaluation. In the “green building” assessment tools, the scales are generally predetermined, i.e. created by the developers of the method. This may be appropriate for “objective” values, i.e. where there is a consensus about their respective importance. Discussions of techniques for weighting are also limited. In the environmental oriented approaches, weighing is either based on expert judgement, on the concept of “willingness to pay”, or on political goals. The link between the measurement of attributes and the weighting (which is important in the simple additive weighting method, see sections 6.3, 6.6 and 6.7), has not received much attention in any of the surveyed literature of the approaches that applies this concept. A further discussion of measurement and weighting techniques is given in sections 6.6 and 6.7.

Advocates of the type 1 approaches (i.e. no scoring or weighting) argue that people tend to reject an opaque numerical process, trusting more in their own ability to weigh factors and come to a decision. They also claim that the weighting and scoring processes tend to hide important details, thus making the decision-making process less transparent. For example, the American system analyst Hugh J. Miser writes (Miser and Quade 1988):

All of these weighting approaches suffer from two important drawbacks: they combine the large spectrum of information developed by the analysis into a single measure, therefore acting to conceal its details from any parties at interest who do not participate in the weighting process; the weights, although they may be acceptable to the analyst and the decision-maker, may not represent the weights that might be assigned by the larger community.

The second objection may be valid in the case of public buildings, or for building where the users are not known. However, in the case where the client is a private company that is going to occupy the building, the objection is not justified. In any case, there will be value judgements inherent in the design decisions. In my view, it would be better to make the value judgements explicit, so that outsiders can see what and who’s values are included, than to just leave them “floating in the air”. Even though a weighting procedure is applied, the details of the performance measurement could still be revealed. This defies the first argument about concealing details.

Another objection against the weighting methods is that people may find it difficult to express their weights with respect to different objectives. Another American system analyst puts it like this (Quade 1995):

It is generally much easier for a group of decision-makers to determine which alternative they prefer (perhaps for different reasons) than what weights to assign the various impacts.

This may be true, but it does not necessarily produce a good decision. If there are many different objectives and conflicting interests, it is not easy to structure everything in your head and come to a conclusion that you feel comfortable is the right one.

In any case, I believe that a formal way of expressing performance scores and weighting values, will produce more discussion among design team members than if the scoring and weighing is just done implicitly. Therefore, a formalized process is more likely to produce new insight and uncover values and biases among team participants. This view is supported by Kirk and Spreckelmeyer, who has applied decision-analysis approaches in practical building design:

In a practical application the process of scoring should generate much discussion, causing participants in the process to focus on the interpretation of the criteria they have defined in addition to assessment of options. It will often come to light that the same words have very different meaning for different individuals, which can lead to a restructuring of the model. The process of setting end points on the scales can lead to an active search for alternative options, spurred by the feeling of "Can we not do better than that".

Scaling the objectives of a problem in this manner not only helps the design team arrive at uniform measurement scales but is also a way to define the general nature and context of the problem. The process of defining and constructing these measurement scales involves the collective participation of the entire team and allows each team member to express his or her own values and expertise to the group as a whole. The establishment of the five scalar points represents not only a convenient measuring device for a decision-analysis exercise, but also presents a visible and public statement of the feeling about a specific design criterion that is shared by the design team. If, at a later stage of design, someone disagrees with the circulation scale or new information shows that the scale is incorrect, a mechanism has been created to allow the team to adjust this definition and to reach a new consensus. (Kirk and Spreckelmeyer 1993).

There is also a discussion about whether or not qualities could or should be quantified. Some argue that qualities are subjective values, hence they can not be transformed into an (objective) numerical scale. Others argue that measuring takes away the focus from the most important thing, i.e. the process of improvement. Edward S. Quade writes (Quade 1980):

Actually, even our ideal measure is defective, for we should be talking about learning, not grades, if we remember what's important rather than what's measurable.

However, it is a fact that people do use quantitative measures for some properties of buildings. Bryan Lawson's before mentioned criticisms of "the numerical measuring disease", also implies that people even tend to put more weight on the factors that can be quantified. (Lawson 1997):

Perhaps it is because design problems are often so intractable and nebulous that the temptation is so great to seek out measurable criteria of satisfactory performance. The difficulty for the designer here is to place value on such criteria and thus balance them against each other and factors which cannot be quantitatively measured.

Regrettably numbers seem to confer respectability and importance on what might be quite trivial factors.

In my view, this is an argument that should lead us to either quantify the qualitative values or make quantities qualitative. The American architect William Peña argues in favor of quantification (Pena 1987):

We know all the reasons why we should not quantify quality too – it's subjective, it's based on value judgements which is different in every individual. It's not scientifically accurate, and so on. Nevertheless everyone, particularly users, judge our buildings – the ultimate products of our services. That's primarily why we are interested in evaluating our own intermediate products…..A symbol such as a score is a good way to immediately perceive a situation. For that reason, we need to quantify quality – to have a score.

The Dutch decision analyst Freerk A. Lootsma argues that measurement techniques must be useful because they have widely been used for grading students (Lootsma 1999):

The assignment of grades has been current practice during many centuries. Although we do not assert that it is a perfect system, it has extensively been used for the evaluation of alternatives (students) under a variety of criteria (subjects or courses), and the decisions to be made were important.

It is a fact that building designers use value judgments that are important for the final outcome of the project. Building designers also use different numerical measures as a basis for decisions about what systems to choose. The crux of the problem then, is how to combine the data and expertise from the different designers in such a way that the goals of the client are best fulfilled. It is difficult to compare different types of criteria, like some say you can't apples and oranges. However, sometimes we have to choose between them, we can't get both the best apple and the best orange. An apple and an orange can be characterized by some common criteria: size, shape, taste, aroma, color, seediness, juiciness, etc. The strength of our preference for these criteria may vary. It may vary with our mood at the time of selection, it may vary according to the use of the fruit, i.e. for display, for eating, for making a cake, etc.

When no formal approach is used, much of the background for the decisions will be hidden inside the heads of the different experts. It is difficult for the other members of the design team, as well as the client, to see what assumptions one expert has made. It is my hypothesis that the outcome of the project would be better if the expert judgements are revealed and documented through a formal approach. To be able to reach a conclusion, different values have to be compared and traded-off against each other. Transforming all values into a common numerical scale may not be the best and only answer to this problem. Nevertheless, using numbers to measure properties is a way to communicate about values that everybody can understand. The process of creating numerical measures for different values may promote discussions about assumptions and values, reveal hidden value judgments, and promote understanding. It may also help structure the discussion and to focus on the issues that are of most importance. Therefore, I think a formal, unified approach based on numerical scales and weights deserves a chance. Yet, one should not expect that everybody would feel comfortable with it in the beginning. Hence, a stepwise procedure, starting with the simplest and most intuitive approaches, is recommended.

The conclusion, then, would be that an evaluation process should start with the type 1 setup, i.e. making a side-by-side comparison of alternatives with respect to criteria, using individual performance indicators (similar to the scorecard model). If there is an obvious choice that emerges from this model, the analysis could stop here. Otherwise, the next step is to measure the attributes on a common scale, weight the criteria, and produce an overall measure of goodness for each alternative. This process should produce a lot of discussion about judgements and values, which may lead to new or revised design alternatives. The process may then be repeated.

Thus, a discussion of how to measure and aggregate a range of different attributes is called for. Within the field of decision analysis there is a range of so-called *multi-criteria decision making (MCDM) methods* where the measurement and aggregation of attributes are the central issues. The next section explores these methods.

6.3 MCDM Methods

Multiple Criteria Decision-Making (MCDM) methods include Multiple Objective Decision Making (MODM) methods and Multiple Attribute Decision Making (MADM) methods.

MODM methods are concerned with the identification of a preferred alternative from a potentially infinite set of alternatives. Options are not defined explicitly, but implicitly by a set of constraints. By far the majority of MODM approaches use mathematical programming in some way, see for example (Hwang and Masud 1979) or (Caballero, Ruiiz et al. 1997).

MADM is defined as "*making preference decisions (e.g. evaluation, prioritization, selection) over the available alternatives that are characterized by multiple, usually conflicting, attributes*" (Yoon and Hwang 1995). MADM methodology is designed for problems that are concerned with the evaluation of, and possibly choice between, discretely defined alternatives.

The MODM methods do not easily fit into a practical building design framework. This is first of all due to their rather complicated mathematical form. The use of computers may facilitate this, but still it is important that the users understand the theory behind the methods in order to use them correctly. Also, the MODM methods require explicit formulation of constraints and objectives as equations prior to their application. This is difficult to obtain in the case of building design. Moreover, they require a large amount of time to collect data that in the early design phase will have a questionable accuracy. In building design, there is little time and understanding for very sophisticated procedures like these, especially in the early design phase. Also, it is a fact that, in general, there are few practical applications of MODM methods in planning of projects. MADM methods are much easier to understand and apply, and since building design is very much about evaluating different design options, they could be useful. Thus, the rest of the discussion will be devoted to MADM approaches only.

There are numerous MADM methods, ranging from relatively simple and straightforward models to advanced mathematical approaches. However, all MADM problems share some common characteristics (Yoon and Hwang 1995):

- *Alternatives:* A finite number of alternatives are screened, prioritized, selected and/or ranked. The term "alternative" is synonymous with "option", "policy", "action", or "candidate".

- *Multiple Attributes:* Each problem has multiple attributes. A decision-maker must generate relevant attributes for each problem setting. The number of attributes depends on the nature of the problem. For example, to evaluate cars, one may use the attributes "price", "gas mileage", "safety", "warranty period", and "style".

- *Incommensurable Units:* The attributes may have different units of measurement. In the car selection problem, gas mileage is expressed in miles per gallon, ride comfort may be expressed in cubic feet, selling price in dollars, and safety is expressed in a non-numerical way.

- *Criteria Weights:* Almost all MADM methods require information regarding the relative importance of each criterion (objective).

In an article published in "Operational Research Tutorial Papers, 1990", Valerie Belton gives a description of the purpose of Multi-Attribute Decision-Making (MADM) methods[5], (Belton 1990):

It is well known from psychological research that the human brain can only simultaneously consider a limited amount of information. The very nature of multiple criteria problems is that there is much information of a complex and conflicting nature, often reflecting differing viewpoints and often changing with time. One of the principal aims of MADM methods is to help decision-makers organize and synthesize such information in a way that leads them to feel comfortable about making a decision. In addition, the need to justify and explain why a particular course of action was chosen, are reasons for adopting a structured approach.

The context in which MADM is useful does not fit into the traditional optimization paradigm of operational research. The concept of an optimum does not exist, there is no such thing as a "right answer". The aim of MADM methods is to help decision makers learn about the problem they face, to learn about their own and other parties' value systems, to learn about organizational values and objectives, and through exploring these in the context of the problem to guide them through a process of learning, understanding, information processing, assessing and defining the problem and its circumstances.

This description suggests that MADM methods may be useful also in building design. There is definitely a lot of information of complex and conflicting nature. The concept of an optimum does not exist. Most important, MADM methods would be useful if it could really help the design professionals and decision-makers learn about their own and each other's values and judgements, and gain a deeper understanding of the design problems.

A survey of MADM methods has been carried out and is reported in Appendix A. Comprehensive surveys of MADM methods are given in (Hwang and Yoon 1981), (Yoon and Hwang 1995) and (Chen and Hwang 1992). From these surveys, the most relevant methods are selected and described below. As underlined before, one of the most important requirements of a method to be used in building design, is that it is quick, simple and easy to use and understand. Many of the MADM methods involve quite complicated mathematics, thus they do not appear to have the user-friendliness and transparency that is required for use in building design. Nevertheless, it might be possible to use some aspects of the methods and adapt them into a building design framework.

[5] Belton uses the word Multi-Criteria Decision Analysis (MCDA). However, I have replaced it with MADM methods to avoid confusion. Although Belton uses the more general term (MCDA), what she is discussing in the paper is really MADM methods.

According to Valerie Belton (Belton 1990), the MADM approaches can be separated into two major, distinct categories, plus a few individual, fringe approaches. The two distinct categories are the *aggregate value function approaches*, principally developed and applied in the USA, and the *outranking approaches*, principally developed in France and Belgium.

In addition to these two main categories, there are a few simple and intuitive approaches that should be mentioned. These are called *methods for screening of alternatives*, and *ranking methods*.

Methods for screening of alternatives

The ***dominance*** method is based on the concept that an alternative is dominated if there is another alternative that excels it in one or more attributes and equals it in the remainder. The first two alternatives are compared, and if one is dominated by the other, the dominated one is discarded. Next, the undiscarded alternative is compared with the third alternative, and the dominated one is discarded. Then, the fourth alternative is introduced, and so on. In the end, only the non-dominated alternatives are left. Since this non-dominated set usually has multiple elements, the dominance method is mainly used for the initial filtering. The method should be used with care, since it has been shown that some dominated alternatives might overall be better than the non-dominated alternatives (Yoon and Hwang 1995), see Appendix A. Yoon and Hwang therefore suggest using a *conjunctive* method first.

In the ***conjunctive method*** the decision-maker sets up the minimal attribute values he/she will accept for each alternative (cutoff level). Any alternative that has an attribute value less that the minimum level, will be rejected. The cutoff level plays the key role in eliminating the unacceptable alternatives; if the cutoff level is too high, none is left; if the value is relatively low, quite a few alternatives are left after filtering. Hence increasing the cutoff level in an interactive way, the alternatives can, in principle, be narrowed down to a single choice.

The ***disjunctive method*** also requires the decision-maker to establish cutoff values for the attributes. An alternative is chosen if and only if it exceeds a minimal cutoff level. Where only one standard needs to be exceeded, most alternatives will pass unless the standards are set at or near the maximal level. If all alternatives are disqualified, the decision-maker can reduce the cutoffs of one or more attributes and resume the evaluation of alternatives. For example, professional football players may be selected according to this method. A player is selected because he can either pass exceptionally, run exceptionally, or kick exceptionally, etc. The player's passing ability is irrelevant if he is chosen for his kicking ability. While the conjunctive method guarantees rejection of all alternatives with extremely small talent, the disjunctive method guarantees selection of all alternatives with any extreme talent.

Ranking Methods

The ***lexicographic ordering*** method assumes that the criteria can be ordered from most to least important (ordinal scale, see chapter 6.6). The alternatives that satisfy the first criterion are judged with respect to the second criterion and if more than two alternatives satisfy this criterion, a third one is used, and so on down the list until just one alternative is identified. Thus, a unique solution is not guaranteed, and the procedure does not allow any tradeoffs among criteria. Lexicographic ordering does not produce a classification of all the feasible alternatives and not all the information for the full set of criteria is necessarily used. In the process of comparing alternatives for a particular criterion it is possible to take account of measurement errors associated with the estimates for the impacts. For example, a threshold value can be defined which must be exceeded before one alternative is rated more attractive than another. By altering the threshold values for each criterion one can judge if the same alternative consistently appears as the most attractive.

In (NIBR 1975b) two methods called ***simple rank*** and ***ordinal method*** are described. These methods are variations of the lexicographic method.

In the ***simple rank*** method the different alternatives are ranked (first, second, third, etc.), according to their degree of goal-achievement. All goals are assumed to be equally important, and the rankings are added to a total measure for the goal-achievement for each alternative:

Impact analysis variable (indicator)	**1. place**	**2. place**	**3. place**
Global warming	Alternative 2	Alternative 3	Alternative 1
Acidification	Alternative 2	Alternative 3	Alternative 1
Aesthetics	Alternative 1	Alternative 2	Alternative 3
Economy	Alternative 3	Alternative 2	Alternative 1

	# 1. places	**# 2. places**	**# 3. places**	**Rank**
Alternative 1	1	0	3	last
Alternative 2	2	2	0	best
Alternative 3	1	2	1	second best

The alternative with the highest number of first places, is the preferred one.

The ***ordinal method*** is similar to *simple rank*, except that the goals are weighted. The alternative with the highest number of first places with respect to the goal with the highest weight, is the preferred one:

Impact analysis variable	**Weight**	**1. place**	**2. place**	**3. place**
Global warming	4	Alt. 2	Alt. 3	Alt. 1
Acidification	1	Alt. 2	Alt. 3	Alt. 1
Aesthetics	3	Alt. 1	Alt. 2	Alt. 3
Economy	2	Alt. 3	Alt. 2	Alt. 1

	# 1. places and (weight)	**# 2. places and (weight)**	**# 3. places and (weight)**	**Rank**
Alternative 1	1(3)	0	1(4)+1(1)+1(2)	last
Alternative 2	1(4)+1(1)	1(3)+1(2)	0	best
Alternative 3	1(2)	1(4)+1(1)	1(3)	second best

The Median Ranking Method stems from the work of Cook and Sieford (Cook and Sieford 1978). They introduced a distance function as a measure of agreement or disagreement between rankings. The disagreement (indicator) for an alternative A_i to become the k^{th} overall rank is defined as the sum of distances between the

$$d_{ik} = \sum_{j=1}^{n} w_j \left| s_{ij} - k \right|$$

attributewise rank and the k^{th} rank. That is:

where s_{ij} is the attributewise rank of A_i according to the j^{th} attribute and w_j is the weight of the attribute. The next step is to pick the elements in the distance matrix to assign ranks to each alternative; that is choosing the elements in the different rows and columns whose sum is the minimum. This can be accomplished by using the so-called "Hungarian Method" of linear programming. The resulting overall ranking differs as little as possible from all available attributewise ranks. For a further explanation of this method, see (Yoon and Hwang 1995).

Aggregate Value Function Approaches

Belton (1990) describes two major components of a value function – the evaluation of each of the options with respect to the criteria (objectives), known as the ***value functions*** or ***scores***, and scaling factors which reflect the relative importance of each of the criteria, known as the ***weights***. This information is then synthesized to give an initial overall evaluation for each option using an ***aggregation model***.

Value functions and scoring

The value of an alternative with respect to a criterion is measured using some sort of *rating scale* or a *value function*. Sometimes, a "natural scale" exists that captures the important values of the attribute. A natural scale is a scale that is in everyday use and has a common interpretation. Often such quantitative scales are not readily available or are too remotely related to the values of the decision-maker to be useful. Then, qualitative scales may be constructed that coincide with the decision-maker's preferences. A value function may be constructed by converting a natural scale to a value scale by means of relative judgements. Alternatively, if no physical measurement exists, the value scale can be constructed simply by direct judgement. Section 6.6 describes different scaling techniques in further detail.

Weighting

Weights serve to express the importance of each criterion relative to the others. The weight assigned to a criterion is essentially a scaling factor that relates scores on that criterion to the scores on all other criteria. There are numerous weight assessment techniques, some of the most common ones are discussed in section 6.7.

Aggregation models

The aggregation model defines how weights and value functions for each attribute are synthesized in order to find an overall value for each alternative. The simplest one, and by far the most frequently used is the *simple additive weighting* (*SAW*) model:

$$v(x) = \sum_{i=1}^{n} w_i v_i (x_i)$$

where:
v is the overall value of the evaluation object x,
x_i is the measurement of object x on attribute i,
v_i is the single-attribute value function,
w_i is the weight of attribute i,
n is the number of attributes

If additivity cannot be assumed (see below), there are also multiplicative and multilinear models. The simplest multiplicative model requires only the addition of an interaction term. These models are considerably more complicated in appearance, and will not be shown here. Von Winterfeldt and Edwards give detailed descriptions of these models (von Winterfeldt and Edwards 1986).

Belton (1990) distinguishes between different groups of aggregate value function approaches. One group is the *Inverse Preference Methods*. These approaches take as their starting point holistic judgements about the value of alternatives from which they infer a value function, as in the case of *PREFCALC* (Lagreze and Shakun 1984), or a judgment policy as in the case of *POLICY* (Rohrbaugh and Wehr 1978). Due to the high demands on information and complicated value function elicitation procedures, these models are not considered to be relevant for the scope of this thesis.

Within the remaining aggregate value function approaches Belton identifies a number of schools. The most widely used are versions of the *Simple Multi-Attribute Rating Process (SMART)* described by Edwards and Newman (Edwards and Newman 1982), and the *Analytic Hierarchy Process (AHP)* by Saaty (Saaty 1990).

SMART *(Simple Multi-Attribute Rating Theory)* was developed by Edwards (Edwards 1971; Edwards 1977) in an attempt to make a simpler version of the Multi-Attribute Utility Theory (MAUT) described by (Keeney and Raiffa 1976). MAUT incorporates the concept of utility functions, while SMART uses value functions. A utility function differs from a value function in that it also takes account of attitude to risk (through the introduction of gambles, see Appendix A and section 6.4). As a consequence, the value functions are much less complicated and the assessment procedures less complex. Edwards was frustrated by the complicated measurement and elicitation techniques of MAUT, and sought simple and robust procedures instead of theoretical soundness and elegance.

The earliest version of SMART consisted of the following 10 steps:

1. Identify the organization whose values are to be maximized
2. Identify the purpose of the value elicitation
3. Identify the entities (alternatives, objects) that are to be evaluated
4. Identify the relevant dimensions of value (attributes)
5. Rank the dimensions in order of importance
6. Make ratio estimates of the relative importance of each attribute relative to the one ranked lowest in importance
7. Sum the importance weights; divide each by the sum
8. Measure the relative value of each entity (alternative, object) on each dimension on a scale of 0 to 100
9. Calculate the overall values using a weighted additive model (SAW)
10. Choose the alternative that maximizes the overall value

In more recent versions of SMART the structuring steps (1-4) have been emphasized. In particular, recognition of the hierarchical nature of structures of objectives and attributes frequently leads to versions of SMART that make use of value trees and hierarchical weighting procedures. Variations of SMART differ in the specific techniques for constructing single-attribute values of the objects under evaluation and in the specific method of weighting (von Winterfeldt and Edwards 1986). Different scoring and weighting techniques are described in sections 6.6 and 6.7 .

***AHP** (Analytical Hierarchy Process)* was developed by Saaty (Saaty 1990). The two basic features of the AHP are the formulation of the problem in the form of a hierarchy and the judgement in the form of pairwise comparisons. The hierarchy has at least three levels:

- Top level: Overall goal of the problem.
- Middle level: Multiple criteria that define alternatives.
- Bottom level: Competing alternatives.

When criteria are highly abstract, such as "well being", sub-criteria (or sub-sub-criteria) are generated sequentially through a multilevel hierarchy. An example of such a hierarchy is shown in Figure 6-8.

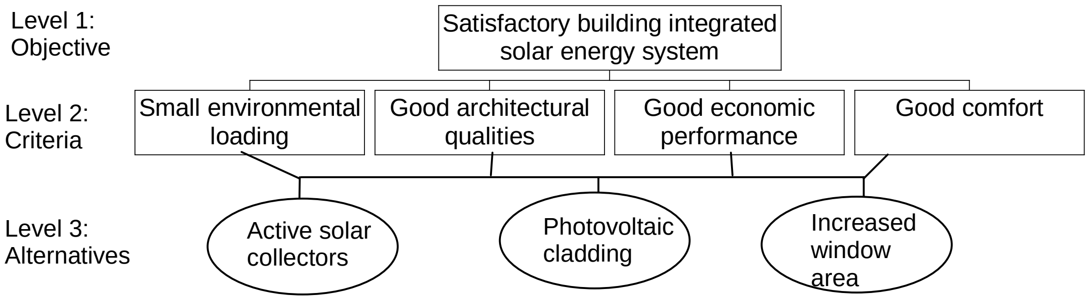


Figure 6-8. Example of a hierarchy of criteria and alternatives as devised by the AHP method.

A pairwise comparison matrix approach is applied to compare elements at a single level with respect to an objective from the adjacent higher level. The process is repeated up the hierarchy. Next, for each criterion a pair-wise matrix of the alternatives is established and for each alternative a score is calculated, using the *normalized principal eigenvector* (see Appendix A). A final score for each alternative is calculated by summing the weighted values for the set of criteria. The alternatives can then be ordered using these scores.

In order to help a decision-maker to assess the pairwise comparisons, Saaty created a nine-point scale of importance or preference, see Figure 6-9. The numbers express degrees of preference between the two elements.

Since it is quite likely that the pairwise comparisons will be inconsistent, Saaty presented the *eigenvector prioritization method* to compensate for inconsistencies of human judgment (see Appendix A).

Numerical values	**Definition**
1	Equally important or preferred.
3	Slightly more important or preferred.
5	Strongly more important or preferred.
7	Very strongly more important or preferred.
9	Extremely more important or preferred.
2,4,6,8	Intermediate values to reflect compromise.

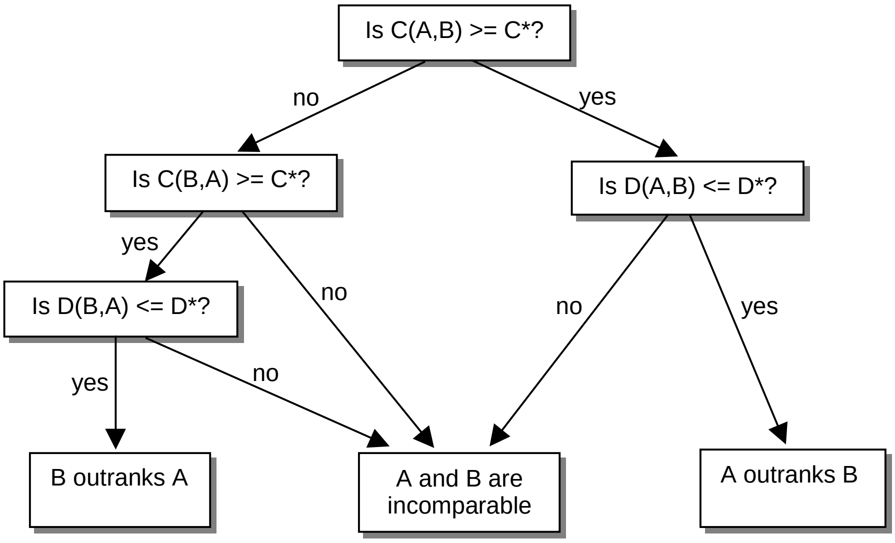
Figure 6-9. The fundamental scale for pairwise comparisons, adapted from (Saaty 1990).

Outranking Approaches

The outranking school of thought differs from the aggregate value function approaches in that it rejects the notion that all alternatives are comparable, maintaining that in some circumstances a decision-maker or group will be unwilling or unable to compare some options. The output is not a value for each option, but an outranking graph indicating preferences, indifferences and incompatibilities. According to Belton (1990), the two most prominent groups of outranking methods are those proposed by Roy et al., (Roy 1973; Roy and Bertier 1973; Roy 1977; Roy 1978; Roy and Hugonnard 1982; Roy 1985) known as the ELECTRE methods, and those proposed by (Brans, Mareschal et al. 1986), known as the PROMETHEE methods.

ELECTRE II (Roy and Bertier 1973) is one of the earliest and simplest of the outranking approaches. The starting point is a set of options evaluated according to specified criteria. The criteria may be weighted to reflect importance. Unlike the weights used in value functions these do not represent trade-offs, but their meaning is not well defined (Yoon and Hwang 1980; Belton 1990). The method is based on the evaluation of two indices, a *concordance index* and a *discordance index*, see Figure 6-10. The concordance index measures the strength of support in the information given for the hypothesis that option A is preferred to option B. The discordance index measures the strength of evidence against this hypothesis. Concordance and discordance indices are determined for each ordered pair of options, A and B. From these indices, an outranking relationship is built (step 3 in Figure 6-10). The threshold levels C* and D* are specified for a particular outranking relation and they may be varied to give more or less severe outranking relations. The selection of threshold levels is arbitrary and is not based on any theoretical or practical grounds (Massam 1988), (Yoon and Hwang 1995).

1. For each pair of options, A and B, calculate the concordance coefficient, C(A,B), and the discordance coefficient, D(A,B).
2. Set thresholds of concordance, C*, and discordance, D*.
3. For each pair of options determine if A outranks B, and B outranks A, or A and B are incomparable, using the following tests:



4. The thresholds C* and D* can be varied to give more or less severe outranking relations.

Figure 6-10. Building an outranking relation in ELECTRE II, from (Belton 1990).

The ***PROMETHEE*** methods were developed by (Brans, Mareschal et al. 1986) and involve defining a preference function for each criterion, utilizing the information about differences in performance. The preference function describes the intensity of preference for option A over option B as a function of the difference in evaluation on that criterion. The function takes values between 0 and 1 and a number of standard shapes have been selected (Belton 1990). A preference matrix $P_j(A,B)$ can be crated for each criterion j. The next step is to determine a preference index for A over B. This is defined as:

$$P(A,B) = SUM_j\ (P_j(A,B))/N \quad or \quad P(A,B) = SUM_j\ (w_j P_j(A,B))/SUM_j(w_j)$$

N is the number of criteria. Criteria weights w_j may be introduced, as shown in the right equation. As with the ELECTRE methods these weights do not represent scaling factors, but some notion of global importance. If weights are introduced the preference index should be normalized by the sum of weights rather than the number of criteria.

The method uses this information to determine the value of two indices, the *positive outranking flow*, $Q^+(A)$, and the *negative outranking flow* $Q^-(A)$:

$$Q^+(A) = SUM_X P(A,X) \qquad Q^-(A) = SUM_X P(X,A)$$

The positive outranking flow expresses the extent to which A outranks all other options, *X*. The negative outranking flow expresses the extent to which A is outranked by all other options. These indices are then used to construct a partial order of the alternatives.

Discussion

The dominance method and the conjunctive method may be useful in order to screen out inferior alternatives. For example, the decision-maker may decide that all design options that have an initial cost above a specified level, are unacceptable no matter how high it scores on other criteria. The disjunctive method may be used to screen out the most promising alternatives by specifying a performance standard for all attributes that needs to be exceeded in order to qualify for further investigation. However, neither of these methods will solve the problem of conflicting values. Therefore, these methods will not help us all the way to the end.

The advantages of the ranking methods are that they are easy to apply, they involve no numerical computation (except for the median ranking), and they are easy to explain and justify in terms of a priority ordering defined on the aspects. The main disadvantage is the non-compensatory nature of the selection process. The ranking methods do not guarantee that the most preferred solution is found. Also, if more specific preference information is available, like interval or ratio data (see section 6.6), this can not be utilized in order to get a finer differentiation between alternatives. In building design, there are normally several parameters that can be quantified, for example cost data and energy consumption. If these data are transferred to an ordinal scale, a lot of information will be lost. On the other hand, there may be contexts in which ranking methods provide good approximations and could thus serve as useful simplification procedures.

Bernard Roy developed ELECTRE because he was critical to the utility function and value function methods on the grounds that they require all options to be comparable. He describes the ELECTRE methods as providing weaker, poorer models than a value function, built with less effort, and fewer hypotheses, but not always allowing a conclusion to be drawn (Roy 1977). Roy and Bouyssou (1986) admits that ELECTRE "*has no axiomatic basis, and consequently it is often difficult to interpret certain parameters in it*". They add, "*only considerations based on common sense allow the decision-maker and the analyst to give them a numerical value*".

By using outranking methods, some incomparable actions become comparable because realistic information exists, but other actions remain, nevertheless, incomparable. Since a comparison of all alternatives and criteria is necessary to reach a conclusion, these methods cannot help us to the end. Belton (Belton 1990) comments on ELECTRE that *"I feel that the approach is a useful one for roughing out a problem, and possibly identifying a small set of options for further, more detailed analysis. However, the information needed for this is quite substantial."*

The most serious drawback of the outranking methods in relation to use in building design, is that they are very difficult to understand for people that are not experts in the field. Even the experts themselves admit that they are difficult to interpret (see above). The value function approaches are much more intuitive and simple. The most simple and straight forward of the value function approaches is the Simple Additive Weighting method (SAW). Also, the Analytical Hierarchy Process (AHP) is gaining attention.

However, these too are fraught with difficulties. The aggregation of impacts across a wide range of variables may be worrying to decision-makers. Some argue that the worth of a particular plan is not a simple additive function of the worth of the various components or even a readily identifiable multiplicative function, for that matter. This is stressed in a paper by Roy and Bouyssou (Roy and Bouyssou 1986). Some even argue that no multi-attribute formulation can ever capture the subtlety and delicacy of the human mind's ability to compare holistic alternatives (Duckstein, Kisiel et al. 1975; Goicoechea, Hanson et al. 1982). One the other hand, there seems to be a lack of empirical support for this view (French 1988). Also, it has been showed that holistic assessments in practice give weight to fewer attributes than a guided multi-attribute approach (Slovic and Lichtenstein 1977; Fischer 1979).

The Simple Additive Weighting method uses all attribute values of an alternative and applies regular arithmetical operation of multiplication and addition. Therefore, the attribute values must be numerical and comparable. Also, for the method to be strictly valid, the criteria should satisfy the conditions known as *preference independence* and *utility independence*. Preference independence states that the tradeoffs a decision-maker is willing to accept between any two criteria are not dependent on any other criteria. For example, given three criteria: "minimum environmental loading", "minimum cost", and "good aesthetics". If a decision maker is willing to accept a 10% increase in building costs given that he will get 20% lower environmental loading, this should be the case for any implications on aesthetics. Utility independence means that criteria are neither *complementary* nor *substitutes*. Criteria are complementary if excellence with respect to one attribute enhances the utility of excellence with respect to another. Criteria are substitutes if excellence with respect to one attribute reduces the utility gain associates with excellence with respect to other attributes.

The verification of these two conditions depends upon the confidence one can attach to options regarding trade-offs among criteria at hypothetical levels. These types of questions may not be easy to pose to the decision-makers in manageable practical ways. Row and Pierce (Rowe and Pierce 1982) argue that those who are asked to describe indifference levels or trade-offs may not have great confidence in their ability to make the necessary judgements.

While the legitimacy of using simple additive weighting methods may be contested, it is a fact that they are the most commonly used of the MADM methods. This is due to their simplicity and intuitive appeal. Also, several studies have shown that theory, simulation computations, and experience all suggest that the SAW method yields extremely close approximations to very much more complicated non-linear forms, while remaining far easier to understand (Hwang and Yoon 1981).

The AHP has become quite popular, and has found applications in a wide number of fields, recently including decisions about indoor comfort in buildings (Clements-Croome 1997), environmental assessment of buildings (Glaumann and Malm 1998), (Lippiatt 1998), and hydropower plant upgrading (Tangen 1996). In the US, the AHP method has even been incorporated in a standard for decisions of investments related to building and building systems (ASTM 1998), and an accompanying software product is available (Forman, Chapman et al. 1998).

There has been extensive debate about the AHP in the literature, centering on a number of issues with both practical and theoretical significance, see (Watson and Freeling 1982; Watson and Freeling 1983; Saaty and Vargas 1984; Belton and Gear 1985; Belton and Gear 1985; Vargas 1985; Dyer 1990; Dyer 1990; Harker and Vargas 1990; Saaty 1990). The most important drawbacks of the AHP for use in building design are:

- The pairwise comparisons may lead the decision-maker to feel that he looses the overview of the problem. The link between the pairwise comparisons on the ratio scale and the final ranking of the alternatives is complicated. The decision maker focuses on small parts of the problem at a time, and when the overall result is presented, the details of the cause-effect relationship are difficult to see. If the decision-maker does not understand this relationship, the result might be hard to accept. This is perhaps the most serious drawback of the method with respect to it's use in building design.

- When there are many attributes, the number of pairwise comparisons becomes large ($n \cdot (n-1)/2$, where n is the number of attributes). For example, if there are 10 attributes, there will be 45 pairwise comparisons. Thus, the process may be too time-consuming for "busy builders".

- A positive feature of the AHP is that it offers feedback on the degree of consistency between comparisons of alternatives within one attribute. However, this does not necessarily mean that the decision-makers will have no problems in answering the attribute weighting questions consistently. For example, one can wonder whether the questions should be answered with respect to average performance levels or maximum performance levels of the alternatives. In addition to understanding what the attributes actually imply, the relations in the pairwise comparisons must be interpreted in a consistent manner (i.e. the scales must be used in the same way for all attributes). Hence, the decision-maker must achieve a conscious understanding of terms like "moderately more preferable", "strongly more preferable", etc., that is comparable between attributes. Thus, the process of answering the pairwise comparison questions in a consistent way may be exhaustive and confusing to decision-makers.

The advantage of the AHP is first of all that it offers a formal and logical way of including qualitative values in the analysis. The consistency check may help uncover biases and inconsistencies in judgements. Also, the hierarchical way of structuring the problem may help the understanding of the problem and the value system.

An important advantage of multicriteria methods is that they make subjectivity and judgements explicit. Multicriteria methods allow one to take into account conflictual, multidimensional and incommensurable effects of decisions in a formal way. They may help to uncover and discover values and aspects that would otherwise have been forgotten. A good MCDM method may stimulate discussion among team participants and promote a common understanding of the design problem. In this way they seem to fit perfectly into the framework of this thesis. However, the methods may appear very complex and “foreign” to building designers. Also, the reliability of the methods is questionable, especially when used by someone inexperienced. Experiments done by (Hobbs and Meier 1994) indicate that different MCDM methods can yield significantly different decisions. Studies done by (Srivatava, Conolly et al. 1995) even indicate that the methods don’t always give similar results when used repeatedly in similar context. However, in building design, one can’t expect to find *the one and only right answer* in any case. Therefore, the most important feature of the methods is that they can produce deeper understanding of the design problem. Thus, as long as the users understand the logic and shortcomings of the methodology, some aspects of MCDM approaches may be adapted into a building design framework.

Until now, how to deal with uncertainties or vagueness in the design process has not been dealt with. Therefore, the next section will discuss this. Also, the details of how to measure attributes and weight criteria need further investigation. These issues are discussed in sections 6.6 and 6.7.

6.4 Uncertainty, Risk, and Fuzziness

Uncertainty and Risk

A common way to deal with uncertainty is to ignore it. The need to do away with uncertainties frequently leads people to take too much credit for successes and too much blame for failures, (Dawes 1988).

Building design is concerned with specifying a product that (hopefully) will be used and operated for many years into the future. Consequently, the future costs and benefits that the alternative building designs will bring, include many *uncertainties*. For example, it is hard to predict exactly how the energy prices will develop during the next 30 years, though it is likely that they will rise on an average. The ability to predict and evaluate future consequences of a design option may be crucial for the success of a project. How then, should the uncertainties best be accounted for in the evaluation of design options?

The concept of *risk* is often used in connection to uncertainties. The meaning of risk varies somewhat. Often, risk is associated with highly negative consequences, which rarely occur. Sometimes it means the probability of a negative consequence. In other cases, it may mean the negative consequences themselves. In yet other cases, risk may refer to the statistical expectation of the negative consequences. Most commonly, however, risk refers to the entire spectrum of negative consequences with their associated probabilities.

Risk assessment is often thought of as consisting of two parts: risk estimation and risk evaluation. In risk estimation, one is concerned with identifying the various serious negative consequences of a project or activity, and assigning probabilities to those consequences. In risk evaluation, one appraises the acceptability of the risk.

Mann defines the difference between risk and uncertainty as follows (Mann 1992):

"Suppose that we assume that there are several possible future "states of the world", and that our alternatives will have different levels of performance for each of them. If it is possible to make reliable estimates about the probability of occurrence of the different states of the world, we are faced with a situation of *decision-making under risk*. When no probability estimates can be made, we are in a *decision-making situation under uncertainty*."

There are different way of dealing with risk, some are described in (Mann 1992), (Flanagan, Norman et al. 1989), (Dror 1988), (Bejrum 1991), (Bazerman 1998), and (French 1988). The following brief description is based mostly on (Mann 1992).

Gambles with known odds are situations of *decision-making under risk*. Game theory suggests a criterion for this type of decision based on what one would "win" on the average in the long run if one played the same bet many times over. This long term average payoff is called the "expectation value". It is formally defined as the sum of all possible outcomes (gains or losses), with each outcome multiplied by its particular probability of occurrence, or:

$$EV_j = \sum_{i=1,2...}^{n} O_{i,j} \cdot p_i$$

where:
EV_j = the expectation value associated with alternative j.
$O_{i,j}$ = the payoff or outcome resulting from the choice of alternative j when state of the world i occurs
p_i = the probability of state of the world i occurring.

The decision rule is to select the alternative with the highest expectation value. The argument for the expected value decision rule is that in the long run, decisions made according to this rule will, in the aggregate, be optimal; that is, good and bad random errors will cancel out over time. In gambling, this decision rule has been called the "rich man's strategy" because it may be necessary to endure a long series of losses before achieving the expected large gain. For those who do not have the means to cover such a series of losses, it could be a fatal strategy. Also, there is other evidence that people do not always follow the expected-value rule.

Daniel Bernoulli (1738) suggested replacing the criterion of expected value with the criterion of *expected utility*. Expected utility theory suggests that each level of an outcome is associated with some degree of pleasure or net benefit, called utility. The expected utility of a certain choice is the weighted sum of the utilities of its outcomes, each multiplied by its probability. While an expected value approach would treat $1,000,000 as being worth twice as much as $500,000, a gain of $1,000,000 does *not* always create twice as much expected utility as a gain of $500,000. Most individuals does not obtain as much utility from the second $500,000 as they did from the first $500,000 (Bazerman 1998). In expected utility theory, each choice that we make is viewed within the context of the overall utility that we are currently experiencing and of what that choice would mean to our overall utility in the future.

Kahneman and Tversky (1979) developed a new theory called *prospect theory*. This theory states that we tend to overweight the probability of low-probability events and underweight the probability of moderate and high-probability events (Bazerman 1998). It also suggests that decision-makers tend to avoid risks concerning gains and seek risks concerning losses. Kahneman and Tversky presented data that suggest that "perceived certainty" has a special value to most people. This means for example that individuals may buy insurance not only to protect against risk, but also to eliminate the worry caused by any amount of uncertainty (Tversky and Kahneman 1981). Slovic, Lichtenstein, and Fischhoff (1982) argue that "*any protective action that reduces the probability of harm from, say, 0.01 to zero will be valued more highly than an action that reduces the probability of the same harm from 0.02 to 0.01*", (Slovic, Fischhoff et al. 1982).

When nature's probabilities are not known, or if the states of the world are the results of actions by other intelligent players who try to anticipate our game moves and select their strategies as to yield outcomes in their best interest, we are faced with *decision making under uncertainty*. Decision theory has developed some recipes for dealing with such situations:

- *The MaxMin or MinMax rule*, recommending that one maximize one's minimum gains or minimize one's maximum losses, respectively. This is a pessimistic decision rule, always assuming that the worst situation will happen. Accordingly, the recommendation is to select that course of action for which the worst possible outcome is least undesirable – that is, to "maximize the minimum gains" if the outcomes are defined as gains, and to "minimize the maximum losses" if the outcomes are defined as losses.

- *Hurwicz Alpha: Partial Optimism/Pessimism*. Most people don't consider themselves as complete optimists or pure pessimists, but rather somewhere in between. This means that neither the completely pessimist MinMax/MaxMin decision rule nor its theoretical opposite MaxMax (maximize our maximum gains, not a highly recommended rule) quite represents their true attitudes. Hurwicz proposed a "partial pessimism/optimism coefficient" called "Hurwicz alpha" that incorporates this. The max and min payoffs for each of a player's strategies are plotted on the opposite ends of a graph representing 100% optimism and zero optimism, respectively. Lines are drawn between these extreme payoff points. The decision-maker can now select a point that appropriately reflects his degree of optimism and then read off which alternative is "best", given that attitude.

- *The Equal-Likelihood Criterion* recommend that if probabilities are not known, one should decide on the basis of the expectation value calculated for the assumption that the states of the world are equally likely.

- *Minimizing Regret or Opportunity Cost.* When we have made a move that does not result in the most favorable outcome, we say that we experience regret – we are sorry we did not pick another move that would have produced a better outcome. A measure of the extent of this regret is the difference between the outcome we actually achieved and the best outcome we could have obtained, given the state of the world or the opponent's move that actually occurred. This measure is also called the "opportunity cost". The corresponding decision rule for uncertainty decisions is to "minimize one's maximum regret", that is, to select that alternative *j* whose largest regret over the set of *i* states of the world is smallest.

French shows that none of these decision rules satisfy all the axioms for good decision-making (French 1988), for example he shows that they may lead to different "best" choices. Thus, he rejects the concept of strict uncertainty and suggests that a decision analysis should be based on the concepts of decisions with risk, and then subject the results to a careful *sensitivity analysis*.

Sensitivity analysis is performed by changing the values used for one or more of the factors in the analysis and redoing the calculations or estimations. One aim is to identify the factors on which the results are particularly dependent. Another is to discover how great a change is required to affect the rankings of the alternatives. Usually, the uncertain assumptions are changed twice; once to see how increasing or strengthening them will affect the results; and once to see what lessening them will do. It is common to change one factor at a time. However, this does not necessarily make a fully satisfactory sensitivity analysis. To achieve this, all combinations of the uncertain factors; two, three, four, and so on, must be examined. If there are a large number of uncertain assumptions, this may become excessively time-consuming and expensive. Some form of Monte Carlo sampling of the parameters may then be applied to solve this (Emerson 1969).

Fuzzyness

The value of a potential design solution may be described by attributes that are both qualitative and quantitative. The evaluation of the quantitative attributes may perhaps be based on calculations involving probabilities. However, the qualitative attributes cannot be modeled by this concept. The main problem with representing the qualitative information, is not a lack of information, but the nature of the information. Linguistic characterizations such as "beautiful", "good", and "attractive" clearly have no quantitative base variable. If an event cannot be described unambiguously and is characterized by subjectivity, incompleteness and imprecision, it is called *fuzzy*. Statements such as "the quality of the environment is good", and "the building looks nice" are said to be fuzzy. Consequently, the use of *fuzzy mathematics* has been proposed to model this.

Fuzzy mathematics, stemming from the founding work of Zadeh (Zadeh 1965), has found applications in many disciplines, and has also been incorporated in MCDM approaches. *Fuzzy set theory* tries to encode a concept of set membership that acknowledges ambiguity. The major contribution of the fuzzy analysis is to emphasize that judgements are not precise and to seek to incorporate this in the analysis in an explicit way. A short introduction to the theory is given below, based on (French 1988). Full surveys may be found in (Dubois and Prade 1980), (Kaufmann 1975), and (Negoita and Ralescu 1975).

Consider a classical set, A. Associated with it is a set membership function, $\mu_A(x)$, defined by:

$$\mu_A(x) = \begin{cases} 1 \text{ if } x \in A \\ 0 \text{ if } x \notin A \end{cases}$$

Thus $\mu_A(x)$ may take one of precisely two values, 1 or 0. If we allow ambiguity, that is a degree of membership, then we allow that $\mu_A(x)$ may take any value between 0 and 1, the greater the value, the greater the degree of membership in A and vice versa. For instance, consider the set of tall men. Under classical set theory we should have to define a precise height, say 6 ft, above which a man would be *tall* and below which *not tall*. Thus the set membership function would have the form shown in Figure 6-11 (a). However, if we admit that tallness is a much vaguer concept, then we might feel that the set membership function shown in Figure 6-11 (b) would be more appropriate. Fuzzy set theory formalizes this notion. A fuzzy set is a real-valued function that takes values in the unit interval. This function is called the set membership function.

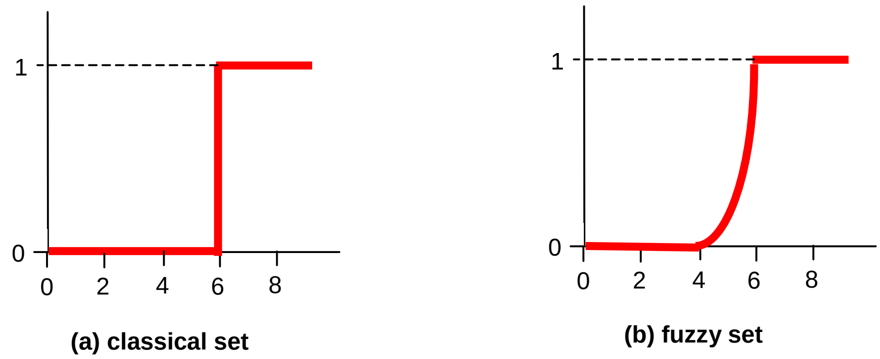


Figure 6-11. Set membership functions for the set of tall men, from (French 1988).

Conclusions

The theories of decision making under risk and uncertainty assume that decision-makers will behave rationally, with the definition of rationality being something like "trying to maximize one's utility" and that such utility can be adequately measured in the payoffs. It further assumes that the payoffs can be predicted with reasonable accuracy in a quantifiable manner. In building design, these conditions are hardly present. Take, for example, the most tangible of the values: cost. It is difficult enough just to establish a reliable estimate of the initial cost, let alone its long-term performance. Given the very limited time and resources of the early design stage, advanced risk assessment procedures do not appear to be realistic. Also, the decision-makers in building design will most likely find the concept of gambles strange and artificial. Moreover, there are intangible values that cannot be modeled using these concepts.

Von Winterfeldt and Edwards (1986) argue that the methods incorporating risk do not enhance the quality of decisions when compared to riskless assessments:

In many practical applications, utility and value functions elicited with risky versus riskless methods are hardly distinguishable because of judgmental errors and because of stimulus and response mode effects.

…there is little experimental evidence for drastic differences between risky and riskless utility functions and there are good theoretical arguments that they are identical…

We would argue then that an analyst should attempt to structure attributes so that they are additive in a riskless sense –and we have not found that to be and exceedingly difficult task.

Some researchers argue that risky procedures are useful because they make the decision-maker think about the decision in the context of the prevailing uncertainties, and that they therefore can help clarify preferences and values (Keeney 1980). This, however, may be adequately achieved through sensitivity analysis.

The fuzzy set theory makes the assumption that the fuzziness in our perception is well modeled by the abstract concept of a fuzzy set. However, the fuzzy analysis is a quantitative theory; numerical values are as much a part of it as they are of any other quantitative analysis. Thus, the qualitative values still need to be quantified, and consequently the fuzzy set theory does not offer a way around this problem. Koulori and Belton recently performed a series of experiments with management science graduate students using a fuzzy multicriteria model (Koulori and Belton 1998). They conclude, "*there is no indication that the human perception of ambiguity is adequately captured by the notion of fuzzy sets*".

Thus, the fuzzy set theory does not offer a way around the difficult problem of quantifying qualities. In addition, fuzzy set theory is hard to understand for people that are not highly skilled in mathematics. Even professionals in the field of decision analysis seem to have a hard time understanding how to use the fuzzy set theory in their field. For example, Simon French comments (French 1988):

How the numbers enters the analysis, what the operations involved mean, how I am to interpret the result: all remain a mystery to me.

Also, Koulori and Belton concludes (Koulori and Belton 1998):

Considering the meaning of membership functions as expressions of preference judgments: we, as our subjects did, have difficulty to comprehend what fuzzy scores mean and what they describe.

For some judgements, relatively simple fuzzy membership may be constructed quite easily. For example, a statement like: *The loss associated with the event x is difficult to predict, but it will surely be less than r_1, much likely between r_2 and r_3, and not greater than r_4*. With the development of efficient algorithms and supporting software it is possible that fuzzy set theory may be of help in the modeling of imprecise judgements in building design. To my knowledge, such tools are not yet available for use in practical, multi-criteria decision making. For use in the early stages of building design, such tools would have to be simple, quick and easy to use.

What seems to be the most appropriate approach for handling risk and uncertainties in the early design stage, is sensitivity analysis. If the uncertain assumptions are not too many, a sensitivity analysis may quite easily be carried out. Through a sensitivity analysis, one will hopefully find a good and robust alternative, that is, one that will perform well even though the future turns out to be different from what is considered most likely. The sensitivity study may also alert the decision-makers that the result relies crucially on a few sensitive parameters, which in itself is a useful outcome.

6.5 Preliminary Recommendations for Multi-Criteria Evaluation of Solar Design Alternatives

To draw conclusions about how a multi-criteria evaluation of solar design alternatives should be carried out, it is useful to review the findings of chapter 2. The most relevant prerequisites for the evaluation part are:

- it should create discussion about values and judgements, to reveal hidden values and biases and to create a deeper understanding of the problem at hand
- it should handle values and judgements and conflicting objectives
- it should be quick and simple to use
- it should handle uncertainties and fuzziness

When evaluating the MCDM approaches, it is important to bear in mind that these approaches are very foreign to the participants in the building design process. Moreover, the time and resources that are available in building design is much more limited than what is common in the settings where MCDM approaches have traditionally been used. Therefore it is recommended to start out with a very simple MCDM-base approach. Then, when this approach has been tried out in the building industry, and the participants have been familiarized with the ideas, perhaps some more advanced methods may be introduced. It is not an ultimate goal to find a method that secures *the* “optimal” answer at all stakes. As discussed before, there is no such thing as an optimum answer to the design problem. However, it is a goal to find the best possible choice within the limited time, given a set of preferences and performances. Hence, the most important prerequisite of the approach should be *to promote discussion about alternative solutions, so that the design team members can learn more about their mission in an effective way, and thus produce a better product.*

Based on these criteria and the preceding chapters, the following preliminary recommendations are given for multi-criteria evaluation of solar design alternatives:

1. A side-by-side comparison matrix is constructed to show the performance of each alternative solution with respect to each of the design criteria. The performance criteria are expressed in their “natural units”, e.g. energy consumption in kWh/m², costs in \$/m², etc.

2. If the number of alternative design solutions are numerous, a screening process is recommended to eliminate alternatives that are clearly inferior. This may be done using the concept of dominance and the conjunctive/disjunctive methods.

3. A ranking method may be used for further screening, and might select the most preferred alternative, especially if one of the following conditions are present: 1) There are only qualitative values to be considered. 2) The qualitative values are much more important or numerous than the quantitative ones.

4. If there are both qualitative and quantitative attributes to be included, convert them into a common numerical scale, weight the criteria, and aggregate the

weights and criteria into an overall measure of goodness for each alternative using a simple additive weighting (SAW) method. The SAW method is simple and intuitive, and it is the most widely used of the MCDM approaches. Although it is not used according to strict theoretical axioms, experience shows that the SAW method agrees well with more sophisticated approaches. Consistency may be checked by posing a few questions regarding trade-offs between criteria. This requires that decision-makers are able to communicate strength of preference judgements. Details about the measuring and weighing procedures are given in the next two sections (6.6 and 6.7).

5. Perform a sensitivity analysis to study the robustness of the conclusion when the most uncertain parameters are varied within plausible bounds.

Thus, for now, it is assumed that the simple additive weighting (SAW) method is the most suitable aggregation method for multi-criteria decision-making in building design. This method, however, requires that the decision-makers are able to make strength of preference judgements. It is also a prerequisite that they can measure performances on different attributes in such a way that the scores and weights can be aggregated in a consistent manner. In the next section, theories and techniques for measuring attributes are discussed.

6.6 Measuring attributes

Measurement theory

Evaluating design options inevitably involve value judgements or measurements. What sort of value judgments can we expect the decision-makers in building design to be able and willing to perform? Preferably, judgements should be performed with ease and accuracy (i.e. be valid and reliable). Almost all decision theorists agree that people presented with two alternatives, A and B, that are to be evaluated against one criterion, can meaningfully say whether they prefer A to B, or B to A, or whether they are *indifferent*. Some theorists go further and claim that people can also communicate about *strength of preference*. Von Winterfeldt and Edwards (1986) take this view and explain it with the following example (the presentation is somewhat simplified from the original):

Imagine you have the opportunity to win one of the following 3 prizes:

1. *Receiving a sum of $100*
2. *Receiving a sum of $500*
3. *Receiving a sum of $10,000*

Consider how you would feel about receiving the amounts. Presumably, all would please you, and you would be more pleased by option 3 than by 2, and more by 2 than by 1. Can you make a meaningful comparison of the intensities of those feelings? Is, for example, the following statement a representative description of your feelings? "Prize 1 would be pleasant to receive. Prize 2 would be somewhat more so. But prize 3 would really delight me; the change in my feelings from 2 to 3 would be much greater than the change in my feelings from 1 to 2." If you find this statement *meaningful, you agree with us that you can make judgments of strength of preference – in the example so far, ordinal ones.*

Von Winterfeldt and Edwards go on to discuss how sophisticated such strength of preference judgements can be. The next step beyond *ordinal* strength of preference judgements, is *ratio* ones. Von Winterfeldt and Edwards give the following test:

Is the difference between 3 and 2 (in attractiveness, not money) more than twice as much as the difference between 2 and 1?

They claim that if you can answer such questions (it makes no difference whether the answer is yes or no), you can make difference or ratio judgements of attractiveness. They further claim that they have no trouble answering the question.

The last step in the measurement ability that von Winterfeldt and Edwards describe is *stimulus ratings*. The test they present to this goes as follows:

Let us define the attractiveness of prize 1 as 0 and the attractiveness of prize 3 as 100. On that scale, how attractive is bonus 2? You may find that question hard to answer. If so, start by asking if 90 would be and appropriate answer. For us, the answer to that question is no. Would 2 be an appropriate answer? For this question, that judgement is difficult, because 2 comes close to being an appropriate rating, but it is a bit too low. Again, by trying out various numbers we believe we can come up with one that expresses our feelings well enough.

Thus, 4 main levels of value judgements may be defined:
Level 1: Preference and indifference judgements
Level 2: Ordinal strength of preference judgements
Level 3: Ratio strength of preference judgements
Level 4: Stimulus ratings

The higher the level, the more difficult it is to communicate the judgements. On the other hand, the higher the level, the more specific are the judgements, and consequently the simpler decision models may be used.

Von Winterfeldt and Edwards (1986) present several arguments to support their view that strength of preference judgements are valid. Of these, I find the following arguments especially convincing:

- Strength of preference judgements greatly simplifies the decision model.
- Empirical evidence shows that strength of preference judgements are not inferior in either reliability or validity to judgements based on preference itself; if anything, it is the other way around.

Taxonomy of Value and Utility Measurement Techniques

Von Winterfeldt and Edwards (1986) categorize the available value and utility measurement techniques by the *stimuli* used and the *response judgements* required. Stimuli can be either riskless or gambles. Riskless outcomes are used in value measurement, while gambles are used in utility measurement techniques. Judgments can either be indifference judgments or direct numerical judgments. According to this, the main value and utility measurement techniques may be categorized as shown in Table 6-5.

Table 6-5. Taxonomy of value and utility measurement techniques, from (von Winterfeldt and Edwards 1986).

Judgements required	**Stimuli**	
	Riskless outcomes	Gambles
Numerical estimation	• Direct rating • Category estimation • Ratio estimation • Curve drawing	• Not applicable
Indifference	• Difference standard sequence • Bisection • Dual standard sequence • Sequential trade-off	• Variable probability method • Variable certainty equivalent method.

In the ***numerical estimation*** techniques the decision-makers are presented with some anchored scale and are asked to rate or otherwise numerically estimate the attractiveness of the stimulus relative to the anchors. These techniques are only used in value function approaches (riskless outcomes).

The ***indifference*** methods for riskless outcomes are based on the notion of strength of preference or value difference. A value functions for one attribute is found by comparing the strength of preference between a pair of attribute levels (a,b) with the strength of preference between another pair of attribute levels (c,d). The pairs are varied until their strength of preference makes no difference to the decision-maker. These methods require that stimuli are densely spaced and that it is possible to vary them in very small steps.

The ***variable probability*** and ***variable certainty equivalent*** techniques are indifference methods in which a sure thing (a so-called certainty equivalent) is matched to a gamble, either by varying the probabilities of the gamble or by adjusting the certainty equivalent.

The methods are further described in Appendix A. The most simple and widely used of the value measurement techniques are the numerical estimation methods. Thus, these are probably the most suitable for use in building design.

Direct rating is the most simple and commonly used numerical estimation method. The decision-maker first selects the worst and the best of the available alternatives for the attribute. Then, the other alternatives are ranked between the two extremes. During the process of ranking, the decision-maker explores how sure he is about his preferences and the reasons for their strengths. Then, the qualitative information is translated into a quantitative value scale. A simple procedure is a numerical rating on a scale such as the one in Figure 6-12. The scale has two anchors; the worst alternative (A) is rated 0, and the best alternative (B) is rated 100. The upper numerical endpoint is arbitrary. The lower one is also, unless ratio judgments are to be used. The remaining alternatives are rated in between. The decision-maker is instructed to consider carefully the relative value of the locations and then rate the remaining alternatives in such a way that the relative spacing between them reflects the strengths of his preferences for one alternative over another. We assume that he tentatively assigns ratings to the alternatives C, D and E as shown in Figure 6-12(b).

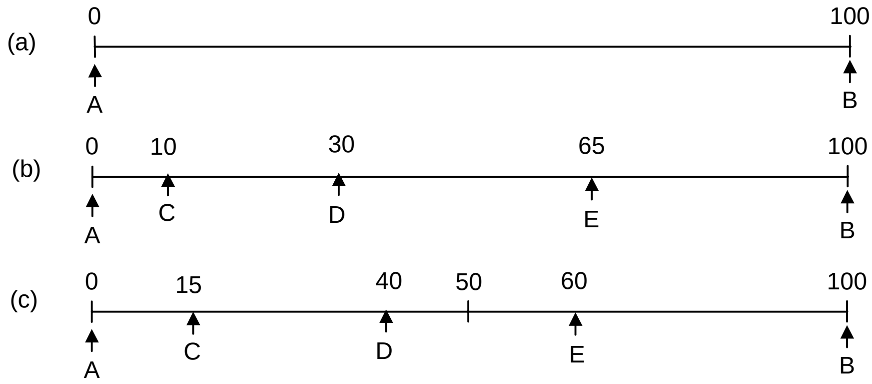


Figure 6-12. Construction of a simple value scale. (a) creating end points; (b) rating alternatives in between; (c) rerating after consistency checks and placing a midpoint. From (von Winterfeldt and Edwards 1986).

Consistency checks can now be made. First, the relative ratings can be cross-checked against one another. For example, the decision-maker may ask himself whether the value steps D-E and E-B should really be equal, as indicated in the ratings. Next, the decision-maker should explore more complex questions such as: Is the difference between alternative C and D truly smaller than between D and E? Finally, the decision-maker can rate a few alternatives not in the original list. Such ratings could refine and enrich the original scale.

The scale construction process stops when the decision-maker feels comfortable with the assessments. The assessments need not be refined to the last digit. Instead it is important that the relative spacings make sense and that the scale has meaning for the decision-maker. If he has trouble placing alternatives on the scale because the meaning shifts from one inter-alternative comparison to another, it may be useful to decompose the scale further. Finally, the meaning of the scale and the justifications of the values of alternatives on the scale should be recorded for further reference.

The *category estimation* method is a variation of the direct rating method. In category estimation, the possible responses of the decision–maker are reduced to a finite number of categories. For example, when judging job locations, the decision-maker may be given the following category scale:

very bad	__	__	__	__	__	__	__	very good
location	–3	–2	–1	0	+1	+2	+3	location

The decision-maker is instructed to sort possible job locations so that the adjacent categories are considered equally spaced in value. The categorization of the scale makes the task somewhat simpler, but fine distinctions may get lost, unless the number of categories is increased.

In *ratio estimation*, one stimulus (e.g. a job) is presented as a standard, and the respondent is asked to compare all other stimuli (jobs) with that standard. For each, the respondent is then asked to state how much more or less valuable that job offer is than the standard, in a ratio sense. Ratio measurement makes sense only if the decision-maker compares increments or losses with a standard (which could, e.g., be the present job). A ratio scale is essentially a difference scale, thus there is a logarithmic relationship between the ratio and the difference information (Lootsma 1999). Sound and light intensities are usually recorded as differences on a logarithmic scale. The dB scale, for example, is logarithmic. With a step of +10dB, the sound intensity is felt to be doubled.

The last variant of numerical estimation is *curve drawing*, which can be used when the attribute has a numerical scale and the decision-maker is knowledgeable about value functions. The value curves may be drawn directly or general function forms may be selected.

Creating Scales

A scale is in essence a means to assign values to each alternative reflecting the contribution to the overall evaluation from their performance on each criterion. Sometimes, “natural scales” exist that may be used to represent the decision-maker’s values. For example, the energy consumption of a building takes a linear, numerical scale that might match the values of the decision-maker. Or, this natural scale may be used as a basis for constructing a value scale, see Figure 6-13. Alternatively, if no natural scale exists, a qualitative scale may be constructed that defines the attribute, its end points, and perhaps some intermediate marker points by means of verbal descriptions. To compare this qualitative scale to a quantitative scale, the qualitative descriptions are associated with numbers that relate the decision-maker’s preferences to the levels of the qualitative scale. This “direct” estimation approach has been criticized because of its lack of theoretical foundation. However, recent studies indicate that a theoretical justification for the quantification of vague meanings of inexact linguistic terms by means of direct estimation can be established (Munda 1995).

Assessment scales may be linear or curved. A linear scale may be used if the preference of a given quality improvement is the same irrespective of whether the quality level is high or low. A curved scale may be used to demonstrate for instance that an improvement on a lower quality level is more valuable than an improvement on a higher level. Figure 6-13 shows examples of linear and curved assessment scales.

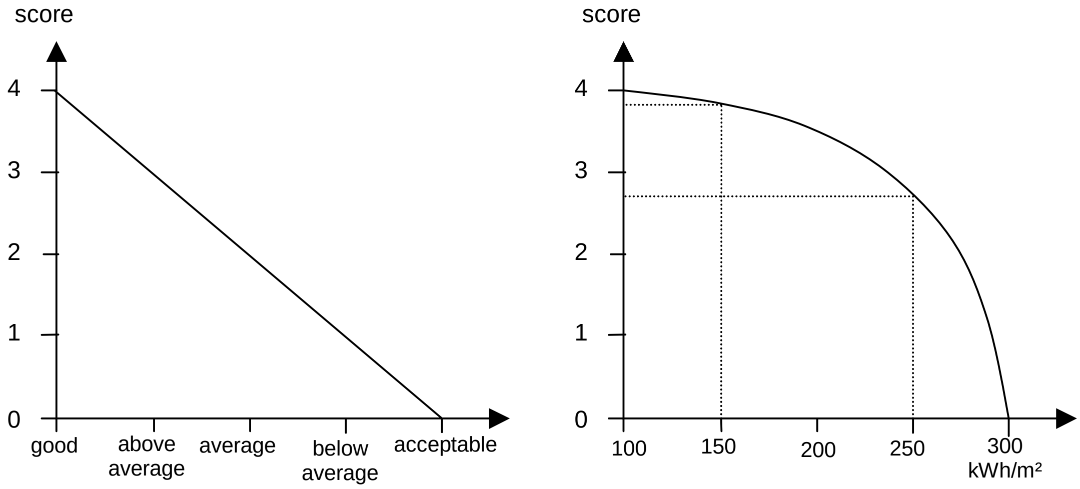


Figure 6-13. A linear scoring curve for a qualitative assessment (left) and a curved scoring scale for an assessment of energy consumption (right). Adapted from (Karnov, Pedersen et al. 1975).

It might be in its place here, to describe the different types of numerical measurement scales that we have. There are three main kinds of numerical measurement scales; *ordinal*, *interval*, and *ratio* (Figure 6-14). An *ordinal scale* measures entities in rank order but tells nothing of the relative distance between ranks. An *interval scale* provides equal intervals between entities and indicates the difference or distances of entities from some arbitrary origin. The *ratio scale* provides equal intervals between entities and indicates the difference or distances from some non-arbitrary origin. The transformation of a qualitative attribute into a ratio scale is very hard. The transformation of a qualitative attribute into the interval scale may also be difficult. It is the ordinal scale that is most easily used for qualitative measures.

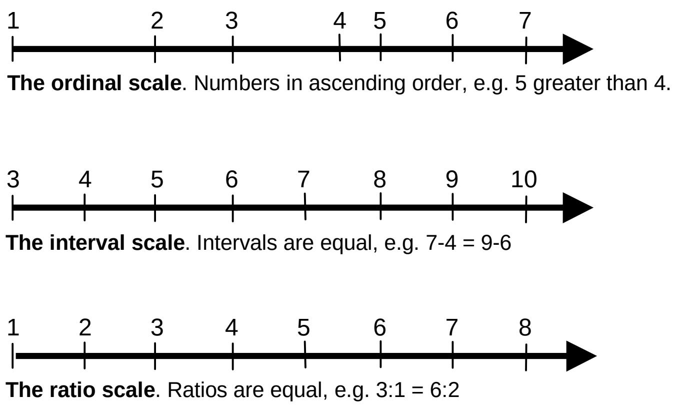


Figure 6-14. The three main types of numerical scales.

Also, it may be useful to note the definitions of *local and global scales* (Belton 1990):

A *local scale* is one that is defined by the set of alternatives under consideration. For example, the alternative that does best on a particular criterion is assigned a score of 100 and the one that does least well is assigned a score of 0. All other alternatives are given intermediate scores that reflect their performance relative to these two end points.

A *global scale* is defined by reference to the wider set of possibilities. For example, the end points may be defined by the best possible and worst conceivable alternatives.

A local scale has the advantage that it can be defined without the need to establish external reference points, which can be a time consuming and difficult process. A disadvantage of a local scale is that if new options need to be considered at a later stage, then some of the scales may have to be redefined, which has consequences for the weighting of criteria.

A special type of scale that has been frequently used in evaluation of qualitative values is the *semantic differential.* This is a list of paired opposite words with a scale between them used to rate the qualities of an object or a place. Usually, the scale is a five point or more odd-numbered scale, unless it is not desirable to have a neutral point in the middle of the scale. Figure 6-15 gives examples of such scales.

static ____ ____ ____ ____ ____ dynamic

warm ____ ____ ____ ____ ____ cool

hard ____ ____ ____ ____ ____ soft

beautiful ____ ____ ____ ____ ____ ugly

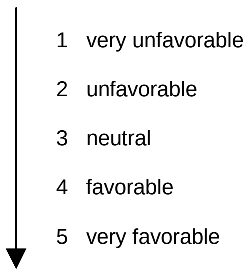
cluttered ____ ____ ____ ____ ____ clean

Figure 6-15. Examples of Semantic Differential Scales. Adapted from (Duerk 1993).

Duerk (Duerk 1993) argues that most novices using this instrument would have a great deal of difficulty developing an interpretation useful for design from a survey using the semantic differential. This is because words have so many interpretations – especially when one's aesthetic judgment comes into play. Also, when there is a mix of qualitative and quantitative assessments, the problem of comparison among attributes still remains.

Yoon and Hwang (1995) suggest the following procedures for comparing qualitative and quantitative attributes: *If the number of qualitative attributes is much larger than the number of quantitative attributes, we convert quantitative into qualitative attributes and apply the Median Ranking method. Otherwise the assignment of numerical values to qualitative data (i.e. by quantification) is the preferred approach.* The Median Ranking method is described in section 6.4.

One of the common ways for conversion of qualitative attributes into an interval scale is to utilize the *Bipolar scale* or the *Linkert-type scale* (McIver and Carmines 1981; Spector 1992). A set of statements, composed of approximately an equal number of favorable and unfavorable statements covering the qualitative attributes, is constructed. For example, a 5-point scale may be chosen, as shown in the figure below. The scale may be calibrated by starting with end points, giving 5 points to the maximum value that is practically or physically realizable, and 1 point to the minimum attribute value that is practically realizable. The midpoint would also be a basis for calibration, since it would be the breakpoint between values that are favorable (or better than average) and values that are unfavorable (or worse than average). However, the points in between may be hard to determine. The decision-maker is asked to pick a statement that best describes the given attribute property.



The Dutch operational analyst Freerk A. Lootsma has presented an interesting model for measuring quantitative and qualitative data on a 7-point scale (Lootsma 1999). The justification of the procedure is based on arguments from behavioral sciences and psycho-physics. Lootsma argues that human beings follow a uniform pattern in many unrelated areas when they subdivide a particular scale into subjectively equal subintervals. Examples are sound (the dB scale), time, and light. The number of subintervals is small because humans have a limited vocabulary. For example, the following verbal terms may be used to categorize prices:

cheap
cheap/somewhat more expensive
somewhat more expensive
somewhat more/more expensive
more expensive
more/much more expensive
much more expensive
much more/vastly more expensive
vastly more expensive

The subintervals are demarcated by a geometric sequence of six to nine grid points corresponding to major and threshold echelons, and the *progression factor* is roughly 2 (see below). This is based on Weber's law of psycho-physics stating that a change in sensation is noticed when the stimulus is increased by a constant percentage of the stimulus itself. This means, for example, that people while holding in their hand different weights, can distinguish between a weight of 20g and a weight of 21g, but not if the second weight is only 20.5g. On the other hand, they can not distinguish between 40g and 41g, but they can between the former and 42g, etc.

Lootsma exemplifies this by a car selection problem. He assumes that the acceptable prices are anchored between a minimum price P_{min} to be paid anyway for the type or class of cars, which the decision-maker seriously considers, and a maximum price P_{max} which he/she cannot or does not really want to exceed. He also assumes that the decision-maker will intuitively subdivide the range (P_{min}, P_{max}) into a number of subintervals which are felt to be subjectively equal:

P_{min}
$P_{min} + e_0$
$P_{min} + e_1$, etc.

Weber's psycho-physical law states that a just noticeable difference in stimulus intensity is proportional to the stimulus intensity itself. The increment above P_{min} is set to represent the stimulus intensity, assuming that the decision-maker is not really sensitive to the performance as such, but to the excess above the minimum:

$$e_v - e_{v-1} = \varepsilon\, e_{v-1} \qquad v=1,2\ldots..$$

which yields:

$$e_v = (1+\varepsilon)\, e_{v-1} = (1+\varepsilon)^2\, e_{v-2} = \ldots\ldots = (1+\varepsilon)^v\, e_0$$

Obviously, the echelons constitute a sequence with geometric progression. The initial step is e_0 and $(1+\varepsilon)$ is the *progression factor*. The integer-valued parameter v is chosen to designate the order of magnitude of the echelons. P_{min} is set to Dfl 20,000 and P_{max} is set to Dfl 40,000 representing the price range for compact to mid-size cars in The Netherlands. The length of the range is Dfl 20,000. Setting the price level $P_{min} + e_6$ at P_{max}, we get:

$e_6 = P_{max} – P_{min}$
$e_0\,(1+\varepsilon)^6 = 20{,}000$ and $(1+\varepsilon) = 2$
$e_0 = 20{,}000/64 \approx 300$

Now, the following scale can be created:

Table 6-6. Performance scales based on geometric progression, adapted from (Lootsma, 1999).

	Numerical performance indicator (price)	Qualitative verbal and symbolic scales			Score (grade)
P_{min}	20000				
$P_0 = P_{min} + e_0$	20300	cheap	excellent	+++	10
$P_1 = P_{min} + e_1$	20600	cheap/somewhat more expensive	good/excellent	++	9
$P_2 = P_{min} + e_2$	21200	somewhat more expensive	good	+	8
$P_3 = P_{min} + e_3$	22500	somewhat more/more expensive	fair/good	0	7
$P_4 = P_{min} + e_4$	25000	more expensive	fair	-	6
$P_5 = P_{min} + e_5$	30000	more/much more expensive	unsatisfactory/fair	--	5
$P_6 = P_{min} + e_6$ (P_{max})	40000	much more expensive	unsatisfactory	---	4

The table also shows that qualitative attributes can be measured directly in this scale, exemplified in the 4th column, using verbal terms like excellent, good, fair, etc, or alternatively using symbols as indicated in the 5th column. A numerical scale from 4-10 is used instead of 1-7 because the grades 1, 2, and 3 are normally used for a very poor performance that cannot be compensated elsewhere, thus they can be ignored. The crucial assumption here is that the decision-maker considers the prices from the so-called desired target P_{min} at the lower end of the range of acceptable prices. From this viewpoint the decision-maker looks at less favorable alternatives.

Some of the scales proposed within the Green Building Challenge project (Larsson and Cole 1998) resemble the geometric scales suggested by Lootsma. As shown in Figure 6-16, the scales have a curved form indicating that the marginal worth of a unit decrease of energy consumption increases as the energy consumption decreases.

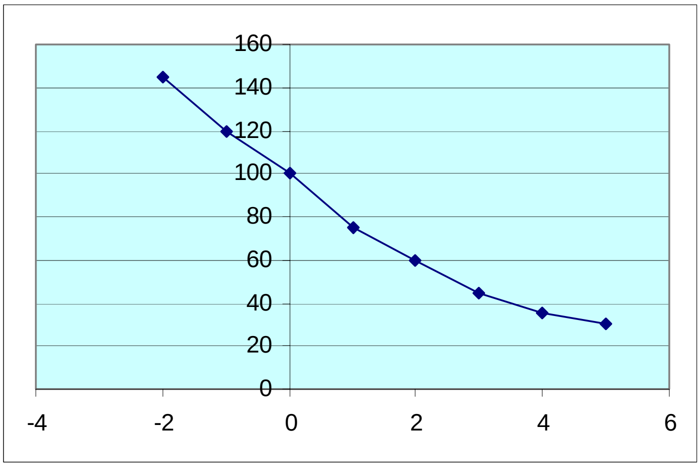


Figure 6-16. Example of performance scale (for operating energy consumption) from the GBC'98 project, based on (Cole and Larsson 1998).

The American architects Kirk and Spreckelmeyer (Kirk and Spreckelmeyer 1993) describe a method that has been used to construct scales for building design objectives. The method makes use of a *design objective scaling worksheet*, such as the one shown in Figure 6-17. Given a particular design objective, design team members are asked to assess the range of extremes that might be acceptable and desirable in a given problem. Questions are posed to the decision-makers to stimulate discussion about the nature of the objective being considered. A question such as *"What is the least you would expect in a potential design solution for how people circulate through this facility?"* might prompt the design team to define the issue of "circulation". The question is repeated for the most desirable value. This allows the decision group to establish the upper and lower bounds of the measurement scale (that is the 5 and 1 values of Figure 6-17). This process is continued for the intermediate points on the scale. Then the intervals between points are tested for accuracy. If the perceived interval between the first and third, and the third and fifth scalar pairs are judged to be equal, then this particular scale can be considered valid. After all comparisons among the various scalar intervals are completed, the circulation design objective scale can be set aside and another objective definition tested. This procedure resembles the direct rating technique described above.

Project: *Corporate Headquarters* **Date:** *3/23/81*
Objective Name: *Circulation* **Objective No:** *1*

Objective Descriptions:

Low value	*1 Extended amount of employee walking for communication. Circulation system that satisfies simple, clear, and direct movement with safety. Mixed circulation for people, vehicles, and service Controlled access to building.*
	2 Tolerable amount of employee walking for communication. Circulation system that satisfies simple, clear, and direct movement with safety. Separate circulation for people, vehicles, and service Controlled access to building.
	3 Moderate amount of employee walking for communication. Circulation system that satisfies job function, personal needs and safety. Separate circulation for people, vehicles, and service Controlled access to building.
	4 Minor amount of employee walking for communication. Circulation system that improves job function and personal needs. Separate circulation for people, vehicles, and service Restricted access to building and parking with separate visitor entry pt.
High value	*5 Minimal amount of employee walking for communication. Circulation system that greatly improves job function and personal needs. Separate circulation for people, vehicles, and service. Restricted access to building and parking with controlled entry points for employees and visitors.*

Figure 6-17. Design objective scaling worksheet, (Kirk and Spreckelmeyer 1993).

Comparing scales - Normalization

In order to get an overall measure of the goodness of each alternative, all the attributes have to be aggregated in a consistent manner. One way to do this is to transform all the data into a common numerical scale by *normalization*. Massam (Massam 1988) lists 5 different ways of normalizing raw data:

1. $\frac{raw\ score}{\Sigma\ all\ scores}$

2. $\frac{raw\ score}{\max\ score}$

3. $\frac{raw\ score - \min\ score}{\max\ score - \min\ score}$

4. $\frac{raw\ score}{\sqrt{\Sigma(raw\ score)^2}}$

5. *Use a transformation function*

Massam shows an example that illustrates that the relative positions between the alternatives remains the same whatever procedure (1-4) is used, but the differences between the alternatives depend on the normalization procedure, see Figure 6-18.

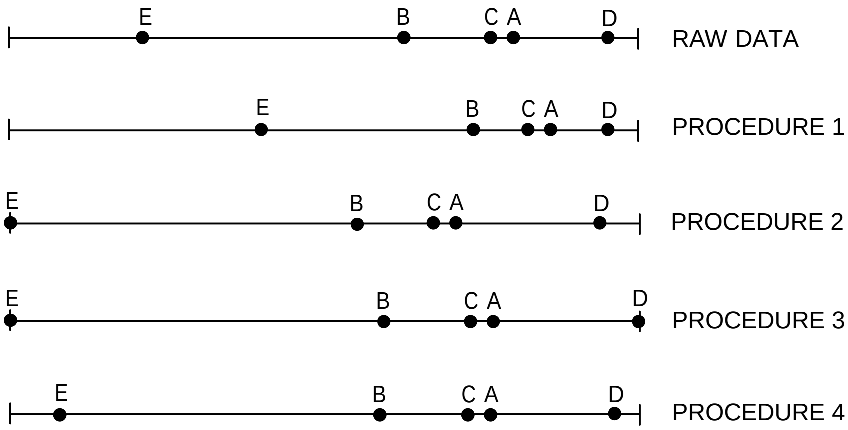


Figure 6-18. Example of normalization of raw data using procedures 1 to 4, adopted from (Massam 1988).

The maximum values in procedures 2 and 3 can be set by using hypothetical or practically acceptable levels, or the maximum value from the raw scores. The fourth procedure tends to put greater emphasis on larger values and hence extends the scale in comparison to the results using procedure 1. The second procedure always gives a value of 1.0 for the highest level and procedure 3 scales all the observations between zero and unity.

The fifth procedure that Massam describes involves a transformation function that converts the raw scores into a scale that range from zero to unity. This scale has been called a *constant worth scale*, a *subjective scale*, or a *utility scale.* The variations of this scale do not necessarily use 0 and 1 as end points. The scale may be non-linear, which in some cases may better reflect the values of the decision-maker. It may for example be that there is a limiting value for a criterion; once this is reached the alternative ceases to be a feasible one, and the utility drops to zero. This can be reflected in the transformation curve. Massam reports that analyst who have used transformation functions as part of an MCDM technique recognize that this allows considerable flexibility and has greater intuitive appeal in deriving the utility values than the other four normalization procedures (Massam 1988). Massam (1988) points out two ways to determine the shape of the transformation curve. First, by direct specification and second, as a result of questioning the decision-makers in order to determine points of indifference on the curves and hence the shape of the function. The first way corresponds to the direct rating technique described above, while the second relates to the indifference methods also mentioned above.

Norris and Marshall report that procedures 1 and 2 sometimes may lead to different final results (Norris and Marshall 1995). Consequently, they suggest using both methods and re-examining any cases where choice of a normalization procedure alters the final conclusions. It is also important to be aware of the fact that normalization is not valid for ordinal or interval scales.

Saaty criticizes normalization on the grounds that it may easily be misused (Saaty 1994):

Among the various number crunching procedures the most pernicious is to assign judgements to the alternatives under a particular criterion. This is done by selecting numbers from some arbitrary set, and then normalizing the numbers (multiplying them by a constant that is the reciprocal of their sum). Generally, the sets of numbers from which the judgments are assigned are different for each criterion. Still, the normalized sets now lie in the interval [0,1], no matter what scale they originally came from, and can be passed off to the uninitiated as comparable.

This is an important point, reminding us that the generation of scales is not an automatic, straight forward procedure, but a careful task in order to find a useful representation of the values of the decision-maker. As will be discussed in the next section, it is essential that the scales are viewed in connection to the weights.

Discussion

In this section it has been argued that it is likely that people are able to make strength of preference judgements. This is grounded in empirical evidence and persuasive illustrations. Different techniques for making such judgements have also been described. The attributes in the evaluation of building design options are very different in nature, and to measure them requires skill and judgement. The crux of the problem is how to measure the attributes in such a way that they can be aggregated in a consistent manner.

Natural scales may be appealing because they are well-defined and readily available. However, the decision-makers should consider whether the scales really reflect their values and how the scales compare to each other. Saaty warns against uncritical use of standard scales (Saaty 1994):

One may be inclined to think that scales of measurement are scientific discoveries that have an objectivity beyond the dimensions they are designed to measure……. But on looking into the history of development of these instruments, one finds that they were invented for convenience and have evolved over a long period of time….. We invent ways to justify their use even when some other property may be the more important.

Keeney argues that the use of any scale requires subjective judgement (Keeney 1992):

Even though the selection of a natural attribute may appear to be completely obvious, it is still the case that the selection involves value judgement… The use of any attribute, even a natural attribute, requires subjective judgment.

Von Winterfeldt and Edwards (1986) suggest that well-defined scales, preferably linear in value, are often useful because they allow the analyst to disassociate the task of measuring the location of the alternatives on that scale from the task of value measurement for the scale itself. Such disassociation, they argue, is particularly helpful when respondents have a strong commitment to one alternative or find it difficult to think of locations in one attribute without considering simultaneous locations in other attributes. Edwards and Newman (1982) state that curved functions are probably often more precise representations of how people feel than straight ones, but such curvature almost never makes any difference to the decision.

In building design it is not possible to find natural, numerical scales for all attributes. In addition, in order to be aggregated, the measurements need to be transformed into a unit that is common to all of them. All the value measurement techniques described in this section may be a means to accomplish this. The strict constraints on time and resources in the early design phase suggest the use of the most simple of the measurement techniques, i.e. the numerical estimation methods. According to Von Winterfeldt and Edwards (1986), these methods have in the past been shown to be reliable, but they may be subject to response mode and stimulus effects. Examples are centering effects (people like to use the middle of a given scale) and spacing effects (people like to space responses equally over the whole scale, no matter what the anchoring points are).

The indifference methods require that the evaluation objects are densely spaced. In many cases, therefore, unrealistic or imaginary alternatives would have to be created in order to get useful results. According to von Winterfeldt and Edwards (1986) these methods may suit sophisticated decision-makers and experts who tend to think in terms of trade-offs and incremental changes. Massam (1988) comments: *While theoretically appealing, it is likely that for practical purposes it is difficult to obtain meaningful results to hypothetical trade-off questions*. Hence, most likely, the decision-makers of the building industry are not yet quite ready for these kinds of methods.

Thus, the numerical estimation techniques seem to be the most suitable, even though they may not be the most theoretically accurate. Von Winterfeldt and Edwards (1986) suggest to start with a direct estimation approach and to use a simplified indifferent method for consistency checking. For example, after rating the attractiveness of an alternative on a 0 to 100 scale, the decision-maker may check whether he truly feels that the strength of preference between an alternative rated at 50 and the 0 anchor is equal to the strength of preference of the 100 anchor over the alternative rated at 50. Nevertheless, this may still be a cumbersome and time-consuming process. It is also important that the value measurement is viewed in close connection to the weighting. The weights are essentially re-scaling parameters that convert all scales into a common unit so they can be aggregated. The scaling technique suggested by Lootsma

(1999) based on evidence that humans follow a uniform way of judging ratios of subjective values as differences of grades, may be a way around this difficulty. This will be further discussed in the next section.

In any case, one cannot expect to get a high degree of accuracy using the most quick and simple of the approaches. However, one must bear in mind that the most important goal of the evaluation process is not to find the absolute optimum choice, but to gain further insight in order to arrive at the best choice given the limited time and resources available. Thus, a simple, but less accurate method can be justified if the users are aware of its limitations.

6.7 Weighting

The weighting techniques can be categorized in a similar way as the value measurement techniques in the previous section, see Table 6-7.

Table 6-7. Taxonomy of techniques for constructing attribute weights, from (von Winterfeldt and Edwards 1986).

	Stimuli used	
	Riskless outcomes	Gambles
Numerical estimation	• Ranking • Direct rating • Ratio estimation • Swing weights	• Not applicable
Indifference	• Cross-attribute indifference • Cross-attribute strength of preference	• Variable probability method • Variable certainty equivalent method.

The simplest way of assessing weight is ***ranking***, that is listing the criteria in order of importance. The most important criterion is assigned a value of 1, and the least important one is assigned a value of n, which is equal to the number of criteria. These ranks can be transformed into normalized weights by several rules, see (Stillwell, Seaver et al. 1981). The most common ones are the *rank reciprocal* weighting and the *rank sum* weighting methods. According to the *rank reciprocal* rule the weight for the i^{th} criterion is calculated as follows:

$$w_i = \frac{1/R_i}{\sum_{j=1}^{n} 1/R_j}$$

where R_i is the rank of criterion i, and n is the number of criteria.

In the *rank sum* weighting procedure, weights are estimated from:

$$w_i = \frac{(n - R_i + 1)}{\sum_{j=1}^{n} (n - R_j + 1)}$$

A typical approach to ***direct rating*** is distribution of 100 points over the criteria so that the number of points assigned to each reflects its relative importance.

In the ***ratio estimation*** procedure, the decision-maker directly estimates how much more important a criterion is than the least important one.

Swing weighting is a procedural hybrid derived from an indifference method in which cross-attribute strengths of preference are systematically compared. In this procedure one determines the weights by matching the strength of preference in one attribute to a strength of preference in another. Similarly, ***cross-attribute indifference methods*** systematically vary alternatives in two attributes to generate simple equations that can be solved for the attribute weights.

The idea of creating indifferences to generate equations that have simple weighting solutions also appears in the ***variable probability*** and ***variable certainty equivalent methods***. In these methods the respondents compare sure things and gambles that have outcomes varying on at least two attributes.

Belton describes an application of swing weighting in value function methods (Belton 1990):
An effective way of weighting criteria is to consider a hypothetical option which is rated zero on all criteria and imagine that you are allowed to increase just one criterion to its maximum level. Which one would you choose? This will be the most highly weighted criterion. Imagine now an option having the criterion you have just selected at its maximum level and all other criteria at zero; then select the criterion you would raise to its maximum level next – it will have the second highest weight – and so on until all the criteria have been ranked. It is important to remember that these weights are dependent on the scales being used for scoring as well as the intrinsic importance of the criteria. If an intrinsically important criterion does not differentiate much between the options then it may be ranked quite low. Having established a rank order assign values to the weights by assigning a weight of 100 to one criterion, possibly the highest rank, possibly the lowest ranked, and then consider each criterion in turn relative to that one bearing in mind the interpretation outlined above. It is generally accepted that these weights are measured on a ratio scale. It is usual to normalize them to sum to 1 or 100.

In their book titled "Enhancing Value in Design Decisions" Kirk and Spreckelmeyer (1993) propose to use a trade-off exercise in order to verify the relative degrees of importance of the objectives (criteria):

The exercise begins with the assumption that decision-makers believe one particular design objective is more important to the success of the project than all other objectives. Assume, for example, that the team has defined and constructed measurement scales for five independent objectives (Figure 6-19) and has determined, for this particular problem, that functional efficiency should take priority. A trade-off diagram similar to the one in Figure 6-20 is constructed for each of the four trade-off comparisons between the functional efficiency objective and the other, less important criteria. A question is posed to the team:

"If circulation and function could be compared one to the other, and if the former were to be increased to its highest scalar value (that is 5), how much of the preferred function objective could be traded off in order to achieve this level of circulation?"

In essence, the group is asked to consider how much of one objective's value can be sacrificed in order to get value from a less important design goal. The distinction of importance between function and circulation is fairly great in this example (Figure 6-20), primarily because the decision-makers in this instance apparently consider the way the building is arranged to be much more important from a functional point of view.

The mechanics for rank ordering design objectives are shown in Figure 6-21. *The completion of this exercise is likely to produce a different rank ordering from that originally expressed by the design team. This is a common outcome of decision analysis and one that should be considered a useful consequence, indicating that a discussion and analysis of the objectives of the problem has produced a deeper understanding of the design project. It is important to remember that the primary goal of decision analysis is not to provide definite answers to complex questions, but to enhance the ability of all decision-makers to comprehend the problem at hand.*

Project: *Corporate Headquarters* **Date:** *3/81*
Location: *Southwest U.S.* **Phase:** *Early Schematic*

Objectives:

No.	Name	Description/Definition	Rank or Weight
1	*Circulation*	*movement of workers and materials in a well-defined manner*	*4*
2	*Functional efficiency*	*organization and arrangement of activities to allow for maximum work productivity*	*1*
3	*Expansion*	*the ability to grow and change within the building and on the site*	*5*
4	*Image*	*comfort of the user in physical and psychological terms, positive corporate image*	*2*
5	*Life-cycle costs*	*minimization of capital, operating, maintenance, salvage, and tax costs*	*3*
6			
7			
8			
9			
10			

Figure 6-19. Initial client and user objectives, (Kirk and Spreckelmeyer 1993).

Project: *Corporate Headquarters* **Date:** *3/81*

Objective “X” Name: *Functional Efficiency* **Objective “X” No.** *2*
Objective “Y” Name: *Circulation* **Objective “Y” No.** *1*

High “X” Objective: *Grouping of functions match organizational needs (in all dept.’s)*
Low “X” Objective: *Clusters of activity areas are compatible in only two dept.’s*

High “Y” Objective: *Minimal employee walking distances. Separate circ. systems*
Low “Y” Objective: *Extended amount of walking. Clear circ. system. Controlled access.*

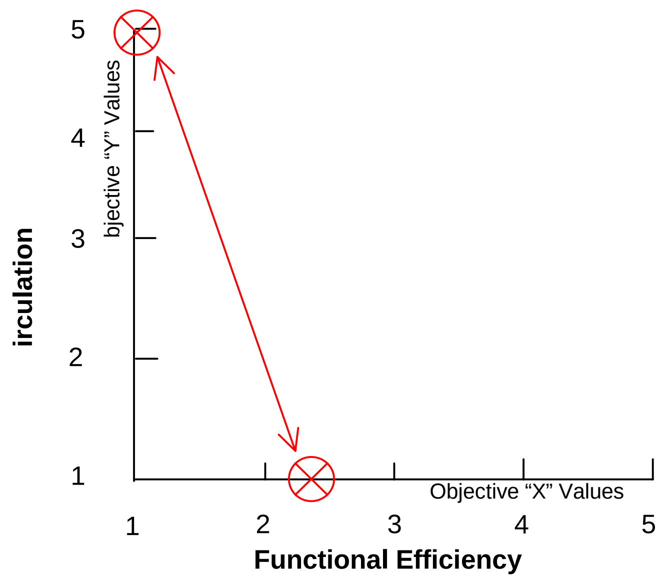


Figure 6-20. Trade-off assessment, (Kirk and Spreckelmeyer 1993).

***Functional efficiency*:** This objective was judged to be the most important. Set the weight at 1.00.	**= 1.00**
***Circulation*:** A trade-off value at the 2.3 points on the *Function* scale was established (see Figure 6-20). Since this point is approximately a third of the distance up the scale, use a weight of 0.33.	**= 0.33**
***Life cycle cost*:** A trade-off value of 3.75 of the *Function* scale was chosen by the team. Since this value is somewhat less than three-quarters of the distance up this scale, use a weight of importance of 0.69.	**= 0.69**
***Expansion*:** A trade-off value at the 3.5 point of the *Function* scale was chosen. This value is just slightly less than assigned to the *Life-cycle cost* goal. Assign a weight of importance of 0.65.	= **0.65**
***Image*:** A trade-off value of 2.3 was chosen. Assign the same weight as *Circulation* at 0.33.	**= 0.33**
Grand Total	**= 3.00**

The new normalized weights of importance of the value statements (in descending order) are:

Function	= 1.00/3.00	= 0.33
Life-cycle cost	= 0.69/3.00	= 0.23
Expansion	= 0.65/3.00	= 0.22
Circulation	= 0.33/3.00	= 0.11
Image	= 0.33/3.00	= 0.11
	Total	= 1.00

Figure 6-21. Weights of importance and rankings of objectives, (Kirk and Spreckelmeyer 1993).

This approach also shows how the attribute scales and weights may be viewed in connection to each other. Another interesting aspect is that it promotes discussion about both scales and weights, and the emphasis on iterations due to increased insight.

Lootsma (1999) describes a way of linking the weights directly to the measurement scales for the impact scores. The starting point is the scoring method described in section 6.6. Lootsma asks us to consider the numerical scale to quantify the relative importance (the weight ratio) of any two criteria. The first thing we want to establish is the range of possible values for the relative importance. Equal importance of two criteria is expressed by the ratio 1:1 of the criteria weights, but how do we express much more or vastly more importance? By the ratio of 100:1 of the criterion weights? In order to answer the question Lootsma carries out an imaginary experiment: The decision-maker is asked to consider two real or imaginary alternatives A_j and A_k and two criteria such that his preference for A_j over A_k under the first criterion C_f is roughly equal to his preference for A_k of A_j under the second criterion C_s. Moreover, it is supposed that the situation is extreme: the impact grades assigned to the two alternatives are 6 units apart under each of the two criteria. That is the maximum distance on the seven-point scales 4,….,10 and 1,….,7. Accordingly, the impact grades assigned to A_j are g_{fj} and g_{sj} and the impact grades assigned to A_k are:

$g_{fk} = g_{fj} - 6$
$g_{sk} = g_{sj} + 6$

If the final grades f_j and f_k are 5 units apart, the ratio $\omega = w_f/w_s$ of the corresponding criterion weights has to satisfy the relation:

$f_j - f_k = 5$

The arithmetic mean aggregation rule is applied to calculate the final grades:

$$f_j = \sum_{i=1}^{m} c_i g_{ij}, \quad j = 1,...n$$

where n is the number of alternatives, m is the number of criteria, c_i is the performance criterion normalized weight, and g_{ij} is the performance grade for alternative A_j with respect to criterion C_i. This yields:

$$\left[\frac{\omega}{\omega+1} g_{fj} + \frac{1}{\omega+1} g_{sj}\right] - \left[\frac{\omega}{\omega+1}(g_{fj} - 6) + \frac{1}{\omega+1}(g_{sj} + 6)\right] = 5$$

This yields $\omega = 11$. Such a ratio implies that the strong preference of A_j over A_k under C_f almost completely wipes out the equally strong but opposite preference under C_s. In addition, Lootsma introduces two new assumptions:

1. The number of gradations to express relative preference for the alternatives equals the number of gradations for the relative importance of the criteria.
2. The numerical values associated with the gradations of relative importance constitute a sequence with geometric progression.

Thus, in the example above, where a *much higher* preference under the first criterion is practically wiped out by a *much higher* preference under the second criterion, Lootsma accordingly refers to the relative importance of the first criterion with respect to the second one as *much higher.* So, a ratio of 8:1 may be taken to stand for *much more* importance. Similarly, if we have a 9 point scale and the impact grades of the alternatives are 8 units apart, Lootsma shows that it yields $\omega = 15$. Thus, he takes a ratio of 16:1 to stand for *vastly more importance*.

A simple geometric sequence of values, with echelons corresponding to equal, somewhat more, more, much more, and vastly more importance, and “covering” the range of values between 1/16, and 16, is given by the sequence 1/16, 1/8, ¼, ½, 1, 2, 4, 8, 16 with progression factor 2. Hence, a geometric scale similar to the one in Table 6-8 is obtained.

Table 6-8. Geometric scale showing the relative importance of criteria (ω). The corresponding arithmetic scale is also indicated (rightmost column).

geometric scale (ratio ω)	description	arithmetic scale (differences of grades, h_i)
16	C_f vastly more important than C_s	8
8	C_f much more important than C_s	6
4	C_f more important than C_s	4
2	C_f somewhat more important than C_s	2
1	C_f as important as C_s	0

If we allow for gradations to express hesitations between two adjacent qualifications in the above list, we have a geometric sequence with progression factor equal to the square root of 2. The ratios of subjective value may be recorded as differences of grades, as shown in the rightmost column of Table 6-8. A difference of 6 units has to represent the ratio 8. This can be achieved with the progression factor equal to the square root of 2. Taking h_i to stand for the grade assigned to criterion C_i, we estimate the ratio of the weights of two criteria C_f and C_s by:

$$\left(\sqrt{2}\right)^{h_f - h_s}$$

An unnormalized weight of C_i is accordingly given by:

$$\left(\sqrt{2}\right)^{h_i}$$

The normalized weight of criterion C_i becomes:

$$c_i = \frac{\left(\sqrt{2}\right)^{h_i}}{\sum \left(\sqrt{2}\right)^{h_i}}$$

Thus, based on the uniform scale presented in section 6-6 (Table 6-6), this shows that it is possible to find a corresponding quantification of the gradations of the relative importance of the criteria. In this way, using the arithmetic mean aggregation rule in a simple additive weighting approach, the relative substitution rate between the criteria is independent of the performance of the alternatives under the remaining criteria. Thus, using these scales, the criteria weighting may be done in isolation from the performance assessment, and those who judge the criteria do not have to be the same persons who assess the performance of alternatives.

Discussion

Criteria weights are indicators of the influence of the individual criteria on the decision. In the value function approaches, the weights are scaling values that define acceptable tradeoffs between criteria – thus they are related to the scales on which attributes are defined. Therefore, the weight assigned to a criterion is essentially a scaling factor which relates scores on that criterion to scores on all other criteria. Hence if criterion A has a weight which is twice that of criterion B, this should be interpreted that the decision-maker values 10 value points on criterion A the same as

20 value points on criterion B and would be willing to trade one for the other. Or put another way, the decision-maker should be indifferent to a trade between 1 unit of A and 2 units of B.

The most simple and intuitive of the weighting approaches, i.e. the ranking, direct rating and ratio estimation methods, all rely on the notion of attribute importance. This concept has been criticized because it assumes that decision-makers are able to appropriately adjust the importance judgments in relation to the scales. Von Winterfelt and Edwards (1986) give an example to illustrate this:

Think about evaluating alternative proposals for abating acid rain. Consider the attributes cost of abatement and percentage of trees in the United States that will die as a result of acid rain. Preserving the trees is obviously very important compared with abatement costs if the policies lead to somewhere between 0 and 50% dying trees and all cost relatively little. However, if the range of dying trees is between 0 and 2%, the relative importance of that attribute should decrease, as long as the range of abatement costs stays the same. The problem is that direct judgement of importance may be insensitive to the ranges of the scales under consideration, and thus importance may distort the rescaling of single-attribute value functions. Without explicit consideration of the ranges, a respondent is likely to state, "The danger to U.S. forests is more important than abatement costs". That statement would, of course, be absurd if it turned out that saving three or four trees cost billions of dollars.

Von Winterfeldt and Edwards (1986) states that the evidence on whether or not people can appropriately adjust the importance judgements, is mixed. However, they list three ideas that may help elicit this problem:

1. Use the natural ranges that the decision-makers have in mind – if need be, elicit them first.
2. Be very explicit about the range you are using; make sure the decision-makers know what it is and understand the relation between ranges and weights.
3. Don't change ranges in midstream. Once you have picked a range that defines 0 and 100, stick with it, even if some new options score –50 or +275 on that attribute because your initial choice of ranges was unwise.

Von Winterfeldt and Edwards (1986) also describe an alternative solution to the range problem; to give up the notion of importance altogether and use *swing weights* instead:

Swing weighting goes a long way toward countering the criticism of using extraneous and perhaps even distorting importance judgements. In fact, swing weighting coupled with carefully anchored single-attribute value elicitation techniques is virtually indistinguishable from the methods that are formally appropriate in the difference measurement techniques.

However, it may still be difficult or at least quite time-consuming for decision-makers that are inexperienced with the concepts, to appropriately adjust the importance judgements according to the attribute scales. Then, the method suggested by Lootsma (1999) might be a possible solution. Lootsma shows how verbal scales can be used to measure both quantitative and qualitative attributes as well as criteria weights. The verbal scales are linked to numerical scales that can be aggregated in a consistent manner.

The most important function of the weighting exercise is that it should be a catalyst in the learning process. Therefore, a good weighting technique is one that stimulates discussion among participants and reveals hidden values and biases. It should also be easy to understand and use for the inexperienced building professionals. Thus, it may be wise to start with a simple numerical estimation method (for example a simple rank) that the design team members all feel comfortable with. The link between the weighting and the attribute scales should be made clear. If the decision-makers feel somewhat uneasy that the result really reflects their values, consistency checks must be applied. The process should not follow a straight line from the beginning to the end, it should be iterative. The necessity to go back and re-evaluate the preliminary findings is not a sign of failing, but an indication that the team members have gained new knowledge of the problem.

6.8 Conclusions

The discussion in this chapter gives the following conclusions:

- The structured approaches to performance evaluation may be separated into 3 levels. The least formal (level 1) approach is side-by-side comparison of alternatives described by separate (different) performance indicators. Comparison of attributes and weighting of criteria are not formalized. At the next level (level 2), the alternatives are measured on a common scale, but the weighting is not formalized. The third approach (level 3), also formalizes the weighting. The supporters of the 1st level argue that level 2 and 3 evaluations hide value judgements and make the process less transparent. However, it is my assumption that the higher level methods lead to better documentation of value judgements. This is because participants of the design team are encouraged to reveal their values and judgements to the other members, thereby promoting discussion and documentation. It is recommended to start at the first level, and to go as far as needed towards the 3rd level.

- The MCDM methods are structured approaches that seek to identify the decision-makers' values with respect to multiple criteria in order to help them find the most suitable choice. They seek to make value judgements explicit and may in this process reveal values or biases that would otherwise have been overlooked. In this way they may promote understanding and learning and ease the communication between design team members.

- MCDM approaches have not found a widespread use in the building industry. The few applications that are found use some sort of simple additive weighting approach.

- If the number of alternatives is large, the concept of dominance as well as the disjunctive/conjunctive methods may be useful to screen out inferior alternatives.

- Simple ordinal ranking of alternatives is intuitively best suited for evaluating qualitative data. However, this approach does not always lead to a unique choice. Also, when more accurate quantitative data should be evaluated, ranking methods may not identify the best choice. Nevertheless, ordinal ranking methods may be useful for screening purposes.

- Compensatory MCDM models are probably too complicated to serve as the first step of introducing MCDM methods into building design. Also, the fact that they do not model trade-offs is viewed as a disadvantage. This is because building design is full of conflicting values, and decision-makers really need to make trade-offs in order to reach a choice. It is better to focus on the value trade-offs, to make them explicit and solve them, than to ignore them.

- The Analytical Hierarchy Process (AHP) offers a rational way to evaluate qualitative design issues. The hierarchical structure of criteria helps organize the problem. It also has the advantage of being relatively simple to use, although it may be time consuming if there are many criteria and alternatives to evaluate. However, the method is quite difficult to understand, and the pairwise comparisons may lead decision-makers to loose the overview and feel that they are not in control.

- The simple additive weighting (SAW) method seems to be the simplest and most intuitive approach to aggregating values and performance measures. Also, experience has shown that it yields good results even though it is not applied on a strict axiomatic basis. Therefore, it seems to be the most suitable approach for introduction into building design. It may help to structure the design work, to focus on the most important issues, and to promote understanding and communication among the participants. However, it needs to be adapted to fit the special needs of building design. Guidelines are needed to be able to use it effectively in a building design framework.

- The simple additive weighting approach is dependent on the users being able to employ measurement and weighting techniques in an efficient way. Direct measurement techniques are simple and intuitive and may be used for any kind of attributes in any setting. However, they are sensitive to biasing errors. Also, it is important that the value measurements are viewed in close connection to the weighting. The simplest of the weighting approaches are the numerical estimation methods. Since these types of importance weightings are closely linked to the measurement scales, it is crucial that the weighting is done with the scales in mind. Some simple indifference questions can be used to check that the weighting and scales are matched in a consistent manner. Another solution to this problem might be to use the logarithmic coding procedure as suggested by Lootsma (1999).

- Sensitivity analysis is considered the most suitable approach for studying the effects of uncertainties and fuzzy statements. The existing models for evaluating risk are too detailed and time consuming for use in the early design phase. The concept of fuzzy sets is quite difficult to understand, but may be used to model vague value statements in this context. However, this requires that simple tools for incorporating it into building design are available. This is probably still a long way to go, and is considered beyond the scope of this thesis.

Based on these conclusions, a framework for multi-criteria decision-making in solar design is proposed and outlined in chapter 7. Then, in chapters 9, 10, and 11, tests of the approach will be reported.

Everything should be made as simple as possible, but not one bit simpler.

- Albert Einstein

7 A Framework for Multi-Criteria Decision-Making in Solar Design

7.1 Introduction

The first part of this chapter contains a summary and discussion of the findings in the previous chapters, clarifying the line of argument. Then a review of the different design activities related to the proposed framework, i.e. the discussion in chapters 3 to 6 (problem formulation, generation of alternatives, performance prediction, and evaluation) follows. Finally, a specification of the framework that is proposed for multi-criteria decision-making in solar design is outlined.

7.2 Line of Argument

The preceding chapters have produced a line of argument as illustrated in Figure 7-1. The ***background*** for the work was based on the fact that solar building design needs to address many different design objectives, called *criteria*. These criteria are often quite complicated to deal with (e.g. environmental loading) and may be conflicting. The different design issues and the many different available energy technologies call for different areas of expertise to be involved in the design of solar buildings. Thus, it may be difficult to evaluate the overall "goodness" of a proposed design solution. Also, the communication between design professionals and the client may be complicated.

The ***goal*** of this work was therefore to produce a means for the design team and clients to be able to better understand and handle holistic solar design. A first ***hypothesis*** was that a structured approach to evaluate design alternatives might be a means to this end.

In order to specify an approach that would fit into the building ***design process***, an analysis of design process theory and building design practice was then undertaken. This analysis resulted in the following conclusions:

- Most building design processes start out with no clearly defined goals or criteria of success. Most clients find it easier to give feedback based on a proposed design solution than to come up with performance requirements to an abstract project. Thus, the design problem is explored and defined throughout the design process. The design criteria are refined and discovered through evaluation and feedback on alternative design proposals.

- Design involves a lot of subjective value judgements, and decisions are often based on experience, “gut feeling” or intuition. Design options are evaluated based on quantitative and qualitative performance measures. Each design is unique due to different actors, different constraints, different organization, etc. For these reasons, there exists no objective optimal design solution. Hence, it is impossible to perform a numerical, global optimization.

- Close cooperation between the members of the design team (including the client) is imperative for the success of solar design. It is important that solar energy considerations are included in the early design stages because the decisions taken here are important for achieving a well-integrated solar energy system.

- It is possible to identify some activities that are common to most design processes:

  - problem formulation
  - generation of alternatives
  - performance prediction
  - evaluation

  The activities are very much overlapping and dependent on each other.

- Decision making in design happens mainly through evaluation of proposed design solutions. The ***conclusion*** was therefore that a structured approach for evaluation of alternative design options is useful and important, but it has to be seen in relation to the other design task, i.e. put into a framework.

The next ***task*** was therefore to search for useful ideas for structuring evaluation in the early design stage. The search was concentrated on the building industry and the field of decision analysis. The field of decision analysis was included because evaluation is an important task in decision making.

The ***result*** of the search was that some structured approaches to evaluation were found within environmental planning and the emerging field of “green building” assessment. These methods resembled somewhat the Multi-Criteria Decision-Making (MCDM) methods that were found within the field of decision analysis. The structured evaluation methods were classified into three levels:

1. Side-by-side comparison of alternative solutions using different units of performance measurement
2. Side-by-side comparison of alternative solutions using a common measurement scale
3. Side-by-side comparison of alternative solutions using an overall measure of goodness based on a combination of a common measurement scale and criteria weights.

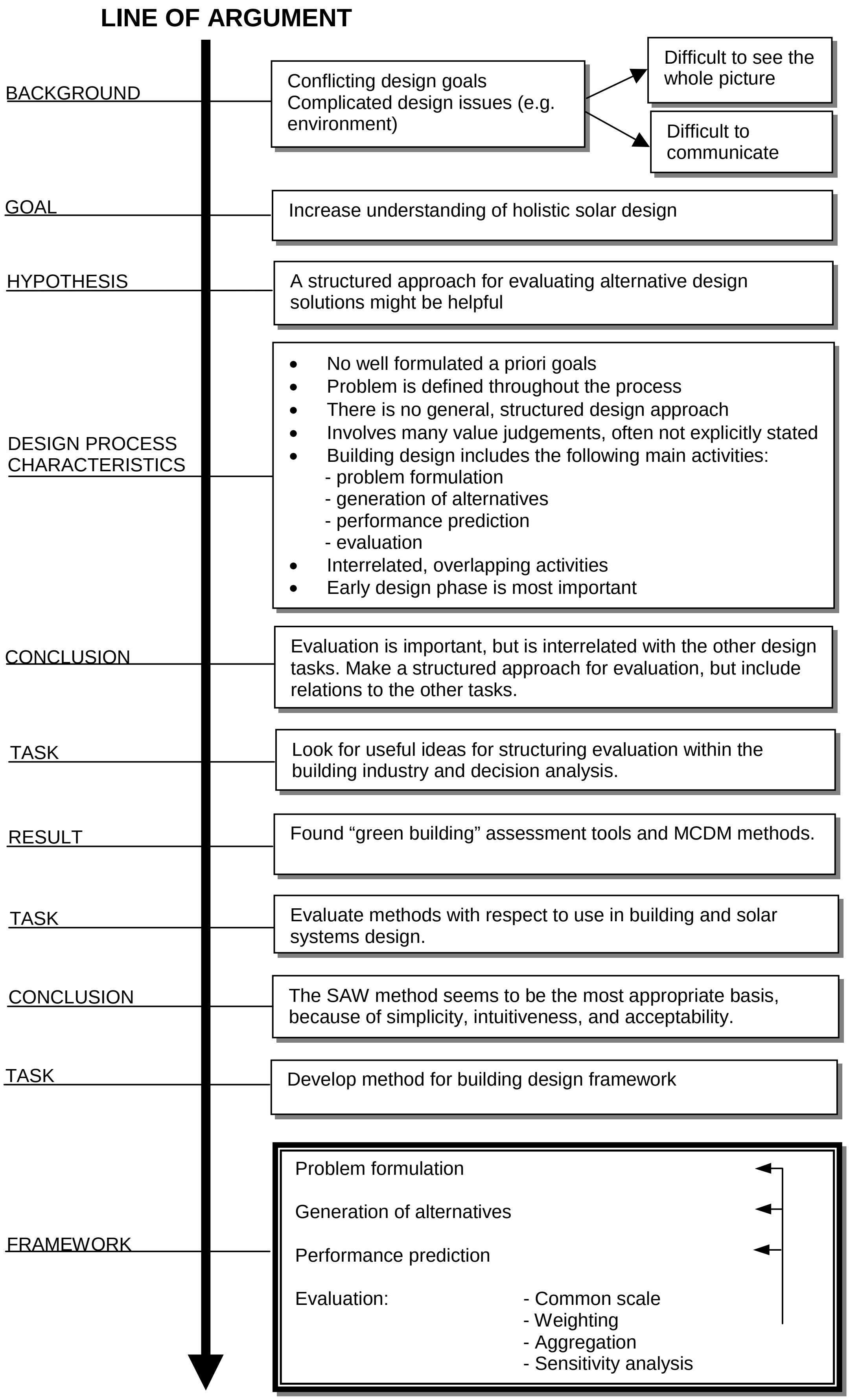


Figure 7-1. The line of argument.

The next ***task*** was then to evaluate these methods with respect to use in building and solar systems design. This evaluation was based on the findings in chapter 2 about the solar building design process characteristics.

The first ***conclusion*** of this evaluation was that a structured side-by-side comparison of alternative solutions seemed to be essential to evaluation. To ensure proper documentation of the performance measures, it was recommended to start with a simple side-by-side comparison of the alternatives according to the level 1 evaluation described above. Such an evaluation may not reveal a clear best alternative. This is due to the fact that the goals are often conflicting or apparently incommensurate. In that case, a level 2 or 3 evaluation is needed. From the survey of multi-criteria evaluation approaches, the Simple Additive Weighting (SAW) approach appeared to be most suitable. Various applications of SAW approaches were found in the "green building" and environmental impact assessment tools. The SAW methods were also found to be the most simple and intuitive of the MCDM approaches. The main advantage of the SAW approach is that it makes value judgements explicit, thereby acting to increase mutual understanding among the design team participants and the client about what is important to focus on. It was also important that both qualitative and quantitative values could be incorporated in the model. The model is also quite flexible, thus it can be tailored to individual needs. A problem of the method is that it is quite difficult to create commensurate measurement scales and elicit representative weights. Therefore, scaling and weighting techniques were investigated in more detail. It was concluded that it might be possible for the design participants to create scales and weights to be used in an evaluation based on a SAW approach that is adapted for the building design process. However, appropriate guidance is needed. Also, some simple screening methods were found to be potentially useful in narrowing the range of alternatives.

Methods for including risk and uncertainty were also evaluated. Formal concepts for this were quite complicated and were considered to be too time-consuming for the early design phase. Still, with the development of advanced computer models, these concepts could be applicable even in early design evaluations. However, a further discussion of this was defined to be outside the scope of this thesis. For the current situation, methods based on sensitivity analysis were found to be the most suitable.

The next section summarizes the conclusions for the 4 parts of the framework (i.e. *problem formulation*, *generation of alternatives*, *performance prediction* and *evaluation*) followed by a section where the framework is specified.

7.3 Problem formulation

In chapter 3, the concept of *value focused thinking (Keeney 1992)* was presented as the basis for generating and evaluating potential design solutions. The crux of this theory is that the values of the decision-makers should be elicited before one goes on to generate and evaluate alternatives. This was based on the view that focusing on alternatives without having the objectives in mind, may limit the possibilities of finding the best alternative. Focusing on alternatives instead of values may anchor the search, limit creativity, and make the search for a solution less effective. However, the idea of values first is an ideal goal, since in practice it is difficult to specify one's values until one has a fair idea of what is possible or feasible. Therefore, in practice, the tasks of formulating the problem and generating/evaluating alternatives are intertwined.

In his theory of value focused thinking, Keeney also implied a hierarchy of objectives, with the fundamental and strategic objectives at the highest level and the means objectives below. The means objectives are derived from the strategic objectives and used to measure the performance of potential solutions. The problem formulation task should contain a discussion of criteria to form a common understanding of what design issues are important and to have a standardized vocabulary that all members of the design team and decision-makers can relate to.

Because of the large amount of information needed to holistically evaluate building concepts, some sort of organization and classification of information into manageable chunks is needed. A survey of models and tools for organizing information in building design was carried out. Checklists, matrixes and hierarchies were found to be the tools most commonly used. Checklists may be helpful as a starting point to get an idea of what issues may be relevant. However, a checklist cannot deal with interactions between its contents at any level of detail. In design of solar buildings, it is important to keep track of interrelations and synergy effects between systems and criteria. A matrix structure provide the possibility to model interactions between pairs of issues, however, multi-dimensional links are difficult to implement. A hierarchical structure seems to be most suited for multi-criteria evaluation of solar building systems. It fits well into the theory of value focused thinking, with the fundamental objectives at the top, and the specific, means objectives at the bottom. It is possible to go into detail without loosing the overview. In a well-structured hierarchy, it is also possible to focus on a part of the problem at a time, because the links to the rest of the system are ensured.

7.4 Generation of Alternatives

The next step that was identified as a prerequisite for evaluation, is generation of alternatives. This is above all a craft, mainly based on creativity, knowledge, and experience. Thus, no general, formal approach can be specified for this task. However, there are some techniques that can be used as aids in the process. Some of these techniques were briefly described in chapter 4 (brainstorming, Delphi, manipulation and pattern techniques). It may be wise to start out with a wide range of ideas that test the extremes of the objectives. This will reduce the risk of overlooking good ideas. The wide range of alternatives may only be evaluated very roughly. Screening techniques, described in chapter 6, may be useful to narrow it down to a smaller set of alternatives that can be evaluated more in detail. The task of generating alternatives may generate new design criteria or it may alter the "old" ones, and as such, this task is very much a part of the iterative loop of problem formulation and evaluation.

7.5 Performance Prediction

The last step that was identified prior to evaluation was performance prediction of potential solutions. In chapter 5, two opposite theories of performance prediction were presented; optimizing and satisficing. Optimizing can be viewed as the ideal way of finding the solution that best fits the objectives. It involves constructing a model that incorporates all parameters and characteristics that have an effect on the optimal solution. Given all feasible values of these characteristics, the model can then predict the optimal solution. However, in practice, such an approach is not possible. This is because such a model would be too time-consuming to construct, and in any case, it is not possible to model all values numerically. Also, the search for an optimal solution would be endless, because there is an infinite number of possible solutions. Therefore, the concept of satisficing is closer to what happens in practical life. Satisficing involves selecting a solution that is "good enough", i.e. it falls within some specified limits of acceptance. However, it is questionable whether this is an approach that is really good enough. While the optimizing approach is too ambitious, satisficing seems to be not ambitious enough. Of course, it depends on what limits of acceptance that are specified; if the limits are ambitious, the solution would be ambitious. However, it is hard to know at what level the limits should be set. The best approach seems to lie somewhere in between the two extremes: to search for a solution that satisfies a set of objectives in a best possible way, given the limited time and resources of the given project. In this process, the decision-maker would have to consider trade-offs between conflicting objectives in accordance with the relative importance of the criteria.

Since available tools for predicting the performance of solar and low energy buildings were described in chapter 2, this chapter concentrated on discussing the level of detail needed. The importance of balance in performance prediction was emphasized. This means that the level of detail of performance prediction should be viewed in relation to the importance of the design criteria. For example, it is fruitless to do a detailed analysis of the embodied energy in the materials, if this is insignificant in relation to the total energy use of the building, or if the decision-makers do not consider energy use to be an important issue. Also, if there are a lot of uncertainties that cannot be modeled, a detailed performance prediction is futile. Moreover, if there are a lot of criteria that can only be evaluated on a coarse, qualitative scale, it may not be worthwhile to measure the other criteria on a detailed scale.

It was also argued that a hierarchical structure of criteria would help promote a balanced performance prediction. A hierarchy divides the problem into different levels of detail, and keeps track of the interactions between issues. In a properly designed criteria hierarchy, one can easily see how improvements in one subsystem will affect the system as a whole. In such a framework, a sub-optimization may even be useful, because it is possible to focus on one limited problem at a time, while keeping track of the relations to the rest of the system. A sub-optimization may be useful to better understand the relationship between a limited set of parameters.

Finally, the presentation of results of the performance prediction was discussed. Several studies indicate that choice is strongly influenced by the way the results are presented. When evaluating building design solutions, it is common to compare the performance to a reference performance, e.g. the average energy consumption for similar buildings, etc. Thus, the choice of reference performance for each criterion will determine if the decision will be positively or negatively framed with respect to the different criteria. It was also emphasized that the presentation should be clear and understandable for outsiders, and it should focus on giving an illustrative overview, while at the same time offer the opportunity to see the details behind.

7.6 Performance Evaluation

The last and most central task of the multicriteria decision-making framework of this thesis, is performance evaluation. Evaluation is comparison of the performance of a potential solution to the design objectives in order to see how well it fulfills these. The evaluation forms a basis for decisions about what strategies to choose. The objectives in building projects are often vague or even unknown. The evaluation process may in itself serve to specify and clarify the design goals. However, even with relatively clearly defined design goals it may be difficult to select the best option because the goals are apparently incommensurate or conflicting. A structured approach to evaluation may help overcome these problems.

In sections 6.2 and 6.3 a survey of structured approaches to evaluation was carried out. The survey revealed 3 different levels of performing a structured evaluation:

1) Side-by-side comparison of alternative solutions using different units of performance measurement.
2) Side-by-side comparison of alternative solutions using a common measurement scale.
3) Side-by-side comparison of alternative solutions using an overall measure of goodness based on a combination of a common measurement scale and criteria weights.

Evaluation requires assignment of “goodness” or “appropriateness” to the predicted performances. Since “good” and “bad” only make sense when there are at least two of a kind, evaluation requires side-by-side comparison of alternatives. A structured way to do this is to make a matrix with the alternatives listed on one “axis” and the criteria on the other “axis”. The cells of the matrix will then contain performance measures for each alternative with respect to each criterion. In this way, the background for the evaluation will be well documented. Also, clearly inferior alternatives may be identified and screened out. In some cases, the best alternative may also emerge. In most cases, however, it will be difficult to identify the best choice because of conflicting and apparently incommensurate goals. Thus, a model for measuring performances on a common scale, weighting the criteria, and synthesizing it all into a common measure of goodness, seems necessary. However, the question of whether or not such an aggregation is fruitful, is raised. Some argue that the worth of a design option is not a simple additive function of the worth of it’s various components. This may be true, but addition still seems to be the most suitable way to determine the overall worth, mainly because it is easy to understand and implement. Others argue that the aggregation hides value judgements and conceals details. To this last argument I have argued that the contrary is true. Since the aggregation requires explicit formulation of measurements and value judgements, it serves to better document the decisions and to promote discussion and common understanding about the design problems. In this way it may help define the general nature and context of the problem. The process of scoring and weighting may also help to identify weak points where the building needs to be improved.

Because it is important that the model can be used in the early building design phase, it should be quick and simple to use. The survey of multi-criteria evaluation models suggested that some sort of Simple Additive Weighting (SAW) approach would be most appropriate. The SAW model appeared to be the most simple and intuitive. Also, most of the evaluation approaches that were found to be applied within the building industry, used some variations of the SAW model. The other models that were found, were either mathematically complicated, very time-consuming to use, or required input data that would be almost impossible to find. The SAW model also seemed to contain the flexibility that is needed in order to be transformed into a building design framework. However, the problem of creating commensurate measurement scales and weights in an efficient and consistent manner, still remained.

Building design involves evaluation with respect to both qualitative and quantitative criteria. The qualitative criteria can only be measured on a relatively coarse scale because humans have a limited vocabulary to describe qualities. In chapter 6, examples of such qualitative scales were given, e.g. *excellent, good, fair unsatisfactory, poor*. The quantitative attributes of a system may be measured in much more detail. Consequently, the quantitative criteria may easily receive much more attention than they really deserve. Also, in the early design phase there is much uncertainty and there is not enough data available to justify very detailed performance assessments. Therefore, it seems most worthwhile to base the evaluation on a fairly coarse scale.

The SAW model requires that the weighting be viewed in connection to the measurement scales. In chapter 6 it was discussed whether decision-makers are able to appropriately adjust the importance judgements in relation to the scales. It was concluded that the evidence about this is mixed. Indifference questions that sort out the decision-makers trade-offs between criteria may be a means to help ensure consistency. However, such checks may be time-consuming, especially if the decision-makers are unfamiliar with the concept or the number of criteria is large. The method presented by Lootsma may be a possible way around this problem. This method offers a way to measure all quantitative and qualitative data on a common, verbal scale. Thus, the scaling exercise becomes easier and quicker as one does not have to do consistency checks. In addition, using this technique, the relative importance of the criteria seems to be a meaningful concept even in isolation from the units of performance measurement. The observation that human beings are sensitive, not to marginal but to relative changes, is grounded in a century of psycho-physical research on the relationship between the intensities of physical stimuli and sensory responses. The concept is also intuitively compelling. Nevertheless, it is a prerequisite that the decision-makers feels comfortable with the scales and that they accept them as representative of their values. The decision-makers may disagree that the geometric progression scale can be used to represent their values, or they may have difficulties in understanding the concept.

7.7 The Framework

It is not possible to make a method that will fit all types of projects. Thus, the suggested methodology will only be a framework or general guideline that should be tailored to fit individual needs and preferences. The main focus of this thesis is on the schematic design phase, because the early design phase is most important for the final outcome of the project. However, the framework may also be used in the later design phases. In Figure 7-2 the framework is illustrated in relation to the design phases. The problem formulation starts in the programming/briefing phase. Here, the first set of design criteria is formulated using the theory of value-focused thinking and a hierarchical organization. Based on these criteria, alternatives are generated and their performances with respect to the different criteria are predicted. The alternatives are then evaluated based on performance scores and weights for the different criteria. The evaluation may lead to a revision of the criteria, or the need for further performance prediction. Thus, there is an iterative loop between the tasks. Evaluation is written in bold types, because the focus of the framework is on the evaluation of alternative solutions. As the design evolves, the principles of the methodology remains the same while the details of the design decisions become more refined. The methodology is applied as often as necessary during each phase in order to solve specific project problems.

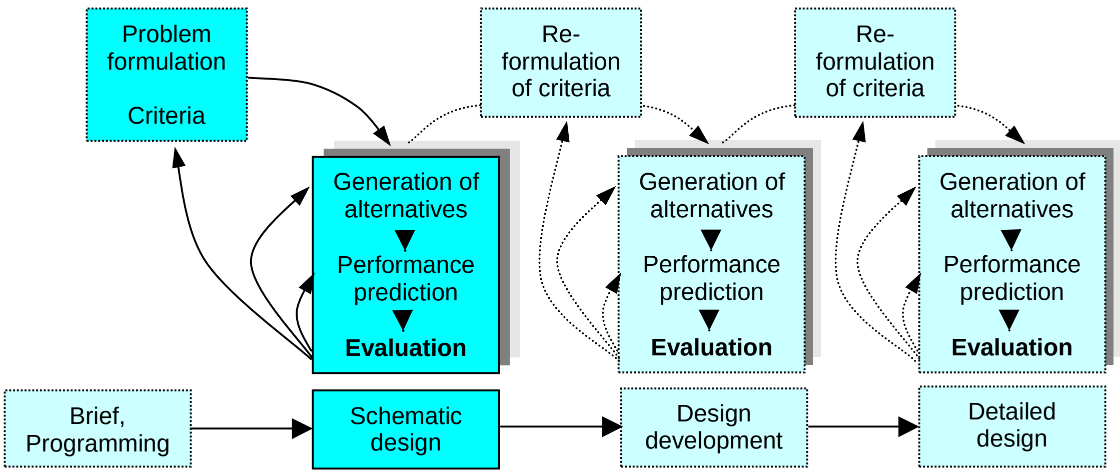


Figure 7-2. The Framework in relation to the design phases.

The framework is primarily directed towards the multidisciplinary design team and the client, but the methodology should be a common point of reference to which all stakeholders can relate. However, there is a need for a central decision-maker that can guide the process. This may be the architect, a representative of the client, or a specially appointed project leader.

Below follows the specification of the different tasks in the framework.

1. Problem Formulation

A hierarchy of design criteria should be developed using the principles of *value focused thinking* (Keeney 1992) outlined in chapter 3. Although it is difficult to specify the objectives before any concrete design alternatives are present, it is important to focus on the values first, not to impose any destructive constraints to the creative process. In value focused thinking, the design criteria are specified using a top-down approach. This means that one starts with defining the higher-level objectives, i.e. the general, strategic objectives of the decision-makers. Then, the more precise, lower-level criteria are specified. Although, it is recommended to start with a top-down approach to eliciting criteria, a bottom-up approach may be useful in the next step of the process. In a bottom-up approach, potential solutions are used to help specifying the criteria.

It is not possible to give a general recipe of what criteria to consider or to what extent they should be included. The number and nature of the criteria will vary from case to case. Generally, it may be useful to focus on the reasons why a criterion is important, and to document this. This will also help clarify the objectives for the different members of the design team and the other stakeholders. For solar and low energy buildings, the life cycle perspective is important. The stakeholders of the building and their present and future needs and requirements have to be projected. The number of criteria and sub-criteria and the level of detail should be chosen based on an estimation of the available time and resources, and the needed accuracy of the evaluation. The following general guidelines may be given:

The criteria hierarchy should be complete and exhaustive. This means that all important performance attributes deemed relevant to the final decision should be represented. The real value attributes should be separated from topics people are merely interested in. One should focus the design effort on those issues that make a major difference in the quality of the outcome.

The criteria hierarchy should contain mutually exclusive items. When eliciting criteria the same concept may arise under different headings. If both are included in the analysis then it is likely that as a consequence the concept will be attributed greater importance. If the hierarchy is restricted to mutually exclusive items, it would permit the decision-maker to view the attributes as independent entities among which appropriate trade-offs may later be made.

In addition, the number of main criteria and sub-criteria must be considered. If there are a large amount of criteria, the problem may be difficult to handle, and one may loose the overview. Also, with a large number of criteria, the importance weights end up small and thus the meaningfulness of the weights is blunted. On the other hand, if there are only a small number of criteria, it may lead to an oversimplification of the real world. The number of criteria may affect the “value balance” of the hierarchy. The greater the level of detail pertaining to an objective, possibly reflected in the number of sub-criteria, the more likely it is that it will be attributed a high level of importance. Miller’s theory (Miller 1956) suggests that it may be wise to limit the number of major and sub-criteria to approximately seven. Miller claimed that seven plus or minus two represents the greatest amount of information that an observer can give us about an object on the basis of an absolute judgement. This theory is widely accepted within behavioral sciences.

Figure 7-3 gives an example of a hierarchy that may be used to evaluate potential solutions for building energy systems. At the top is the overall goal of the design; "the optimal energy system" for this particular building. Then, at the next level follows the main criteria, which are divided into sub-criteria, sub-sub-criteria, and so on. The sub-criteria are presented in separate entities due to space limitations. Also, the criteria are indicated using key words only, e.g. full criteria statements are "minimum environmental loading", "maximum comfort", etc. This hierarchy may have been derived from a hierarchy of fundamental objectives as described by Keeney (1992). Note that some of the sub-criteria are crossed out; this is to show how the final hierarchy has been deducted from a wider, more general one. A more detailed example of how such a hierarchy may be developed is given in chapter 9 (case 1).

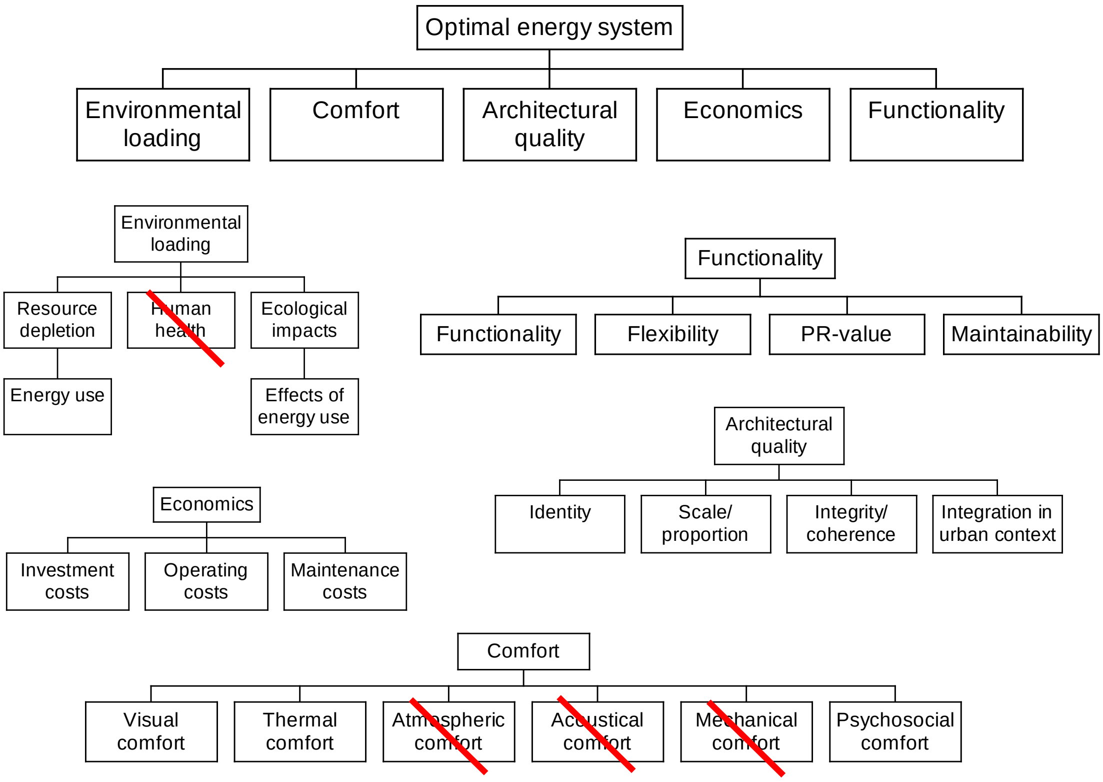
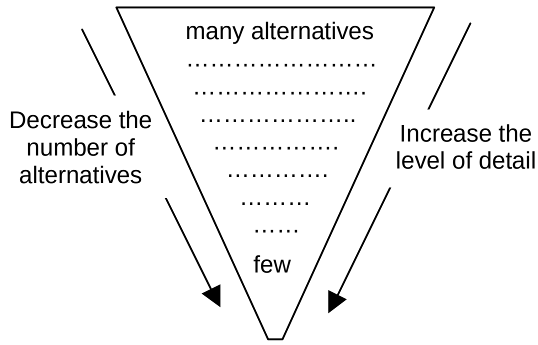


Figure 7-3. Example of a criteria hierarchy for evaluation of energy systems for buildings.

Finally, a simple assessment of the relative importance of the criteria should be carried out in this phase. This will provide a basis for the next two tasks, to help see what is important to focus on when generating alternatives and predicting their performance. This may also help specifying the level of detail for the different branches in the hierarchy. A simple ranking of criteria weights may be sufficient.

2. Generation of Alternatives

Since the generation of alternatives is mainly a craft, little formal guidance can be given for this task. However, it is important that the alternatives are generated based on the criteria and their relative importance. Techniques to promote creativity may be used, e.g. brainstorming techniques. It may be wise to start out wide to test the extremes of the criteria and to be sure that a wide range of possibilities has been considered. Different screening techniques may be helpful, for example simple ranks or the concept of dominance.



The screening of alternatives.

It may be useful to categorize the alternative solutions into main groups and subgroups, according to their purpose or main principles. For example, the main categories for façade systems may be Thermal Collectors, PV collectors, and Windows. An example of a hierarchy of solar systems is given in chapter 9 (case 1).

3. Performance Prediction

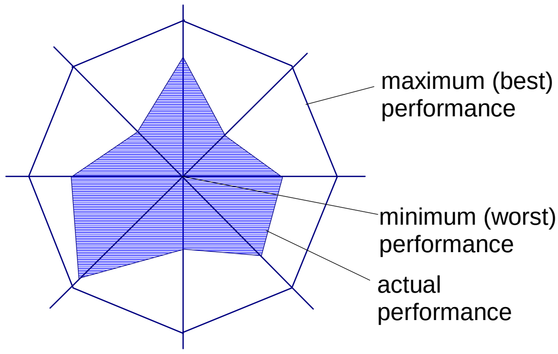
The performance prediction should be done in accordance with the criteria hierarchy. The criteria hierarchy and the preliminary weights dictate the level of detail needed in the performance predictions for the different criteria. In this way, an appropriate and balanced performance prediction may be carried out.

The result of the performance prediction may be presented in a matrix structure to facilitate side-by-side comparison. The matrix should contain descriptions of the alternatives' performances with respect to the different criteria. Different types of performance indicators may be used, i.e. numbers may be used for the quantitative criteria and verbal statements for the qualitative criteria. Uncertainties should be specified, for example by indicating the plausible ranges of deviation from the expected value. Table 7-1 shows an example of such a matrix. At this stage, the results should be presented as objectively as possible, i.e. as "raw data" without any relation to reference values.

Table 7-1. Example of a matrix structure to assemble the performance assessments.

	Criterion 1: energy consumption	Criterion 2: aesthetics	Criterion 3: life cycle cost	Criterion 4: comfort
Alternative 1	200 ± 10%	Overall scale/proportion is well accomplished. Some deterioration of colors may occur.	500 ± 15%	20 hours of overheating in south facing rooms during summer. Some cold draft from east windows in dining area. Good lighting, daylighting….
Alternative 2	…………………... …………………...	…………………... …………………...	…………………… ……………………	…………………... …………………...
Alternative 3	…………………...	…………………...	……………………	…………………...

A so-called "star diagram" has been used to present the overall performance of an alternative, see the figure below. In this diagram it is possible to show multiple dimensions, thus all the individual performance measures can be gathered into one picture. Each "finger" represents the scale for one criterion. The performance on each criterion is plotted on each "finger" (the center of the star usually designates the lowest/worst performance). However, there is a limit to the number of dimensions that can be presented without making the graphics look cluttered. Following Miller's theory (Miller 1956), a maximum of 9 fingers is probably the limit. Only the main criteria should be plotted in the star diagram. The sub-criteria may possibly be indicated below the main criterion.



Star diagram.

Although the star diagram may be used to give an indication of the overall performance of an alternative, it should be used with caution. This is because the performance scales for the criteria are not commensurate; individual scales are used, and no weights are applied to make them comparable. Therefore, it is recommended to show the individual scales on each "finger", to clarify that the scales are not directly comparable.

The next task is to prepare for the evaluation. Evaluation involves measuring and comparing the alternative solutions with respect to the objectives. To measure and compare something, you need to have a reference. The choice of reference is important, because it may have a big influence on the results. Common references are minimum, maximum or mean values. In the case of building design, these may be "least acceptable", "standard/common practice", and "best practice". Alternatively, one of the proposed solutions may serve as a reference. The reference performances may be indicated in the star diagram, as shown in Figure 7-2.

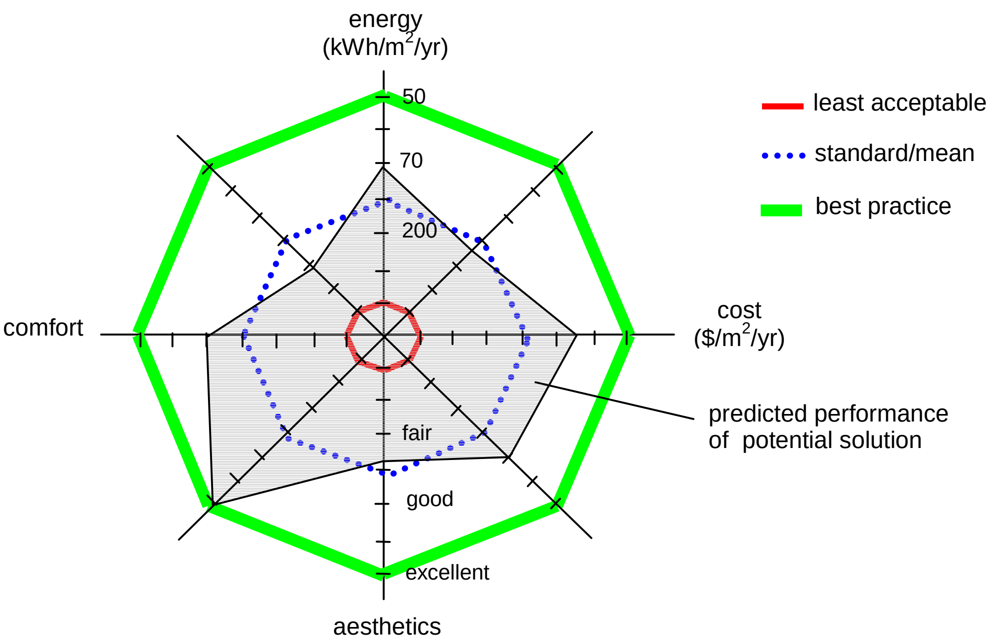


Figure 7-2. Star diagram with individual criteria scores and reference scores indicated.

Task 4: Performance Evaluation

The evaluation process is separated into 4 steps:

1. *Scaling and scoring*: The performances of each attribute are transformed into a common scale.
2. *Weighting*. The criteria are weighted based on the chosen scales.
3. *Aggregation*. The weights and the scores are aggregated to obtain an overall evaluation of each alternative.
4. *Sensitivity analysis*. Sensitivity analyses are performed to test the robustness of the results. Conclusions are drawn and recommendations are made.

It may be necessary to do several iterative loops in this process. Firstly, the weighting may lead to a need to redefine the scales. Secondly, the sensitivity analysis may reveal a need to change both the scales and the weights.

Step 1: Scaling and scoring
The common measurement scale need not have a large number of intervals. This is because fine gradations do not make sense for the qualitative criteria; these criteria can only be described verbally, and humans have a limited vocabulary to express qualitative gradations. Also, for the quantitative criteria, it does not makes sense to have a very fine scale, partly because of the large uncertainties of the performance

predictions in the early design phase, and partly because they should be compatible to the qualitative ones. A 9- or 10-point scale seems to be the maximum usable gradation. When comparing alternatives, we have 5 main terms to express the relative attractiveness of one alternative to the other, see Table 7-2. The categories in between can be used when the decision-maker hesitates between the neighboring qualifications. The 10-point scale is usually reduced to a 7-point scale because the performances that are assigned a score lower than 4 are so poor that they cannot be compensated elsewhere. The 7-point scale has also been widely used within behavioral sciences. Thus, a 7-point scale, with scores ranging from 4 to 10 seems to be most appropriate.

Table 7-2. Verbal terms to express the relative attractiveness of an object.

	relative judgement	**direct judgement**
10	reference	excellent
9		
8	somewhat less attractive	good
7		
6	less attractive	fair
5		
4	much less attractive	unsatisfactory
3		
2	vastly less attractive	poor
1		

The qualitative criteria are rated directly on this scale. When constructing scales for the quantitative criteria, the qualitative scale should be used as a basis. First, the end points should be decided. The end points should be realistic, that is, it should be easy to imagine that some of the alternatives being considered might realistically score at the maximum and minimum value. The scale should be wide enough that it is probable that new alternatives do not fall outside the boundaries, and narrow enough so that the alternatives are well spread out in order to be able to differentiate among them. This can be done by considering the acceptable range instead of the possible range, i.e. the range that one would be willing to consider. For example, if the criterion is “energy consumption”, one could ask the following question to the decision-makers: “What is the best performance of energy consumption you would expect in a potential design solution?” and “What is the least you would accept?”

The scale needs to be divided into intervals that are felt to be equal. There are three different approaches that may be used to determine the points in between the extremes. The easiest approach is to apply a linear scale. However, such a scale implies that our preference follow a linear progression, which is probably not likely, at least not for all criteria. Nevertheless, a linear scale may be a useful approximation. Some experiments suggest that straight-line approximations to curved utilities make little difference to the final decision (Edwards and Newman 1982), (von Winterfeldt and Edwards 1986).

The second approach is to manually subdivide the scales so that the intervals are felt to be equal, e.g. the difference between the first and the third, and the third and the fifth scalar pairs have to be subjectively equal. This, however, might be a cumbersome and time-consuming process.

The third approach is based on the assumption that our preferences follow a geometric progression. In his recent work, Lootsma (1999) presents convincing arguments based on behavioral sciences and psycho-physics, which supports this. He shows that our sensory systems for the perception of sound, light, smell, taste and time all follow geometric sequences that are very similar. Then he shows that this enables us to categorize quantitative values on scales using verbal expressions like fair, good, excellent, etc. The qualitative attributes can be rated directly on this scale. Thus, a link between the quantitative and qualitative scale is established. A prerequisite for this approach is that the decision-maker considers the range of acceptable performance data from the so-called desired target (P_{min} in Table 7-3).

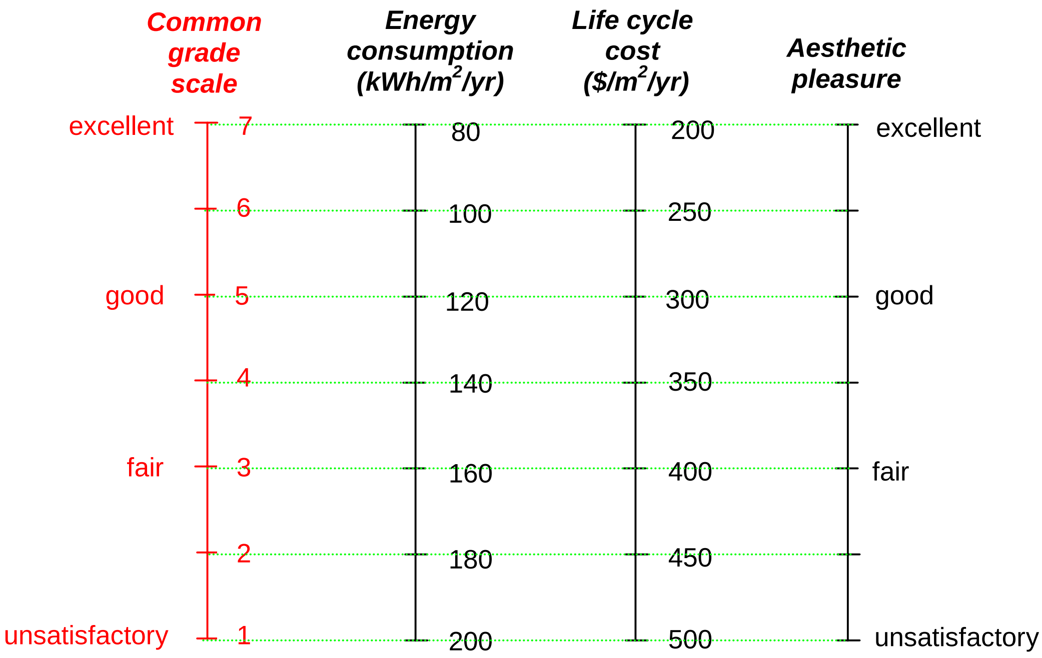
Table 7-3. The geometric progression scale, based on Lootsma (1999).

	Numerical performance indicator (e.g. price)	**Qualitative verbal and symbolic scales**			**Score (grade)**
P_{min} (reference)	20000				
$P_0 = P_{min} + e_0$	20300	desirable	excellent	+++	10
$P_1 = P_{min} + e_1$	20600		good/excellent	++	9
$P_2 = P_{min} + e_2$	21200	somewhat less desirable	good	+	8
$P_3 = P_{min} + e_3$	22500		fair/good	0	7
$P_4 = P_{min} + e_4$	25000	less desirable	fair	-	6
$P_5 = P_{min} + e_5$	30000		unsatisfactory/fair	--	5
$P_6 = P_{min} + e_6$ (P_{max})	40000	much less desirable	unsatisfactory	---	4

The choice of scaling and scoring approach must be viewed in connection to the weighting approach.

Step 2: Weighting

A weight assigned to a criterion is essentially a scaling factor that relates scores on that criterion to scores on all other criteria. This is a subtle idea, and is not always easy to see. Therefore, it may have to be explained to the decision-makers, for example by giving an example similar to the one given in section 6.7. Using the first two scaling approaches described above, the link between the scales and the weights need to be established. Thus, consistency checks have to be made using trade-off questions or indifference questions. The link to the scales may be established by showing the scales and asking the decision-makers about their trade-offs or indifference between the criteria. For example, a set-up like the one in Figure 7-3 may be used. The scales for the different criteria are drawn side-by-side next to the common scale of grades. The trade-offs between the criteria given by the ratio of weights are then checked by indifference questions such as the ones below the scales in the figure.



Given the weight ratio *energy : cost : aesthetics = 2 : 4 : 1*, the following checks may be made:

- The decision-makers should be indifferent to a trade between 4 units of the energy consumption criterion and 2 units of the cost criterion. This means for example that the energy consumption may be increased from *120* to *200 kWh/m²/yr* if the cost is decreased from *300* to *200 $/m²/yr*.
- The decision-makers should be indifferent to a trade between 1 unit of the energy consumption criterion and 2 units of the aesthetic pleasure criterion. This means for example that the energy consumption may be increased from *160* to 180 *kWh/m²/yr* if the aesthetics is increased from *fair* to *good*.
- Etc.

Figure 7-3. Set-up for linking the scales to the weights.

An alternative is to use an approach based on the preference theories of Lootsma (1999), explained in section 6.7. The criteria weights are determined on a 7-point scale similar to the one used for scoring the performances, see Table 7-3 above. This is based on the deduction leading to Table 6-8. The decision-maker can express the importance of criteria in grades on the scale 4,5,…,10, as follows (grades lower than 4 are possible but will practically eliminate the corresponding criteria):

Table 7-4. Grading scale for determining weights.

grade h_i	**description**
10	*Preferred criterion (reference)*
9	
8	*Somewhat less preferred*
7	
6	*Less preferred*
5	
4	*Much less preferred*

The most important criterion receives a grade of 10. All the other criteria are compared to this, e.g. if a criterion is felt to be somewhat less important than the most important one, it receives a grade of 8. The normalized weight of criterion C_i is calculated as follows:

$$c_i = \frac{\left(\sqrt{2}\right)^{h_i}}{\sum \left(\sqrt{2}\right)^{h_i}}$$

Using this approach, the link between the scales and the weights is embedded in the procedure, and does not have to be established explicitly.

Step 3: Aggregation

The simple additive weighting (SAW) model is proposed to aggregate the performance grades and the criteria weights:

$$f_j = \sum_{i=1}^{m} c_i g_{ij}, \quad j = 1,\ldots n$$

where f_j is the final score for alternative A_j, n is the number of alternatives, m is the number of criteria, c_i is the normalized weight of the performance criterion C_i, and g_{ij} is the performance grade (score) for alternative A_j with respect to criterion C_i.

The calculations needed are so simple that a hand calculator is sufficient to produce the result (or it may even be done manually). However, a simple worksheet setup might be useful because the process can be more automated and it gives the possibility to produce graphics to illustrate the results. The results of the evaluation should be presented in such a way that it is possible to trace the weighing and scoring outcomes. Figure 7-4 shows an example of such a presentation where the total scores for the alternatives are shown (top) together with the performance scores with respect to the different criteria (bars – different colored sections), and the weights of the criteria (pie-chart).

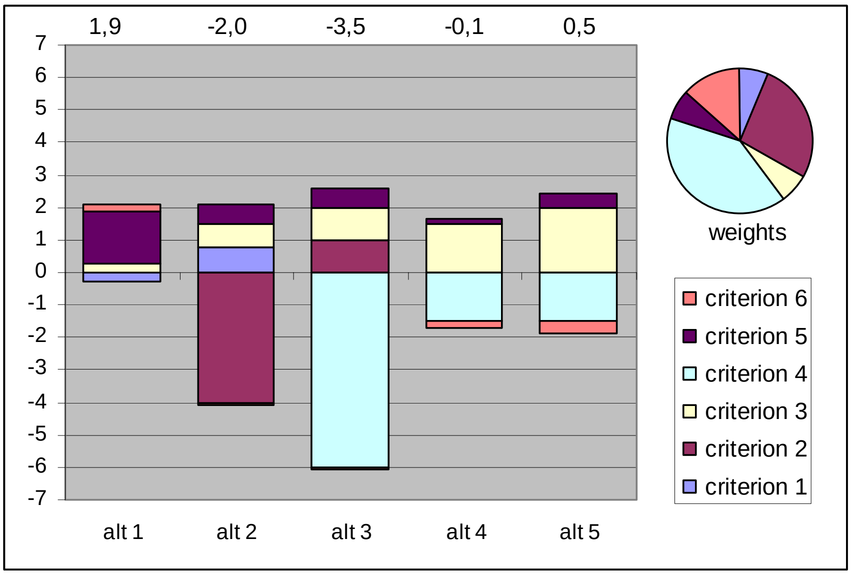


Figure 7-4. Graphical presentation of the aggregation of weights and scores. The scores are indicated on the vertical axis. The numbers above the bars are the total weighted scores for each alternative. The weights are shown in the pie chart at the top right.

Step 4: Sensitivity study

A sensitivity study is a test of the robustness of the results with respect to variations in the assumptions used in the evaluation, i.e. the criteria weights and the performance measures. It would probably be wise to start with investigating the sensitivity to weights. The criteria weights are the essence of value judgements; they very much determine the outcome. Also, the weights are more likely to be in dispute than the performance measures (scores). It is usually sufficient to vary the weights at the higher level of the trees, because the lower-level weights have much less effect on the result. Obviously, one should vary the weights that are most dubious. The next task is to investigate variations of the performance measures. This is only needed if some performance measures discriminate much between alternatives. The result may be tested with extreme values for different future scenarios.

The results of the sensitivity analysis may also be illustrated graphically, for example as shown in Figure 7-5. Here, the weights have been changed, and the resulting bars can be compared to the ones in Figure 7-4.

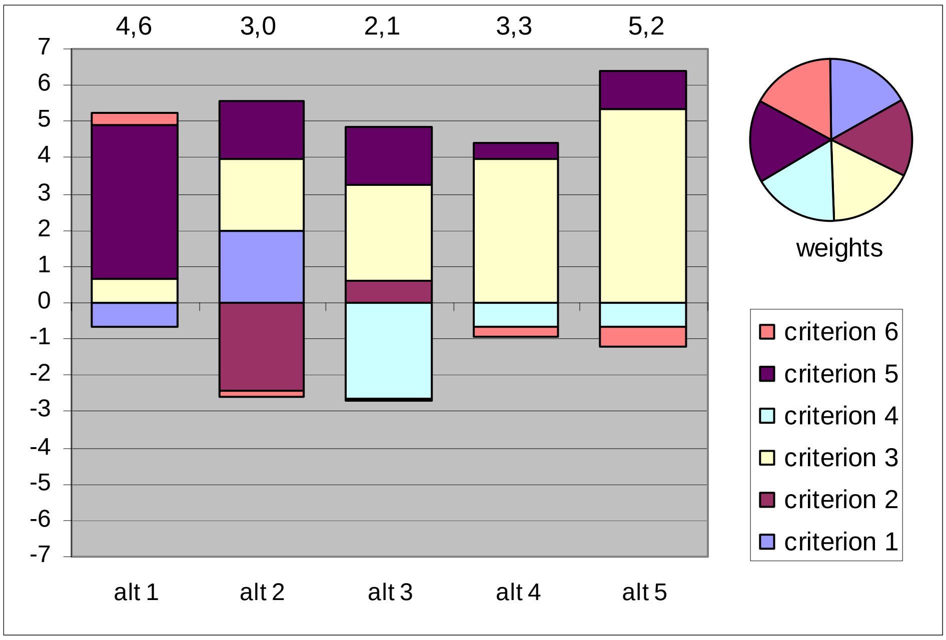


Figure 7-5. Illustrating the sensitivity to weights. The performance scores are kept the same as in Figure 7-4, but the criteria weights are different.

In the following chapters, the suggestions of this framework is exemplified and tested in 3 case projects.

8 Introduction to Case Studies

The tree case studies that have been carried out are somewhat different in nature. The first two case studies were carried out before the multi-criteria decision-making method was fully developed. Also, the first studies are partly theoretical, i.e. they were not fully carried out in real life building design projects. The first case study was done as a part of an EU research project that aimed at designing a generic office building facade based on a-Si photovoltaic panels. Thus, this case study does not match exactly with the target of this thesis. However, the study was still useful because it served to illustrate the use of the method among a group of designers, and it allowed for going into greater detail of documentation than a more "practical" case would have done. In this case the participants created their own measurement scales, i.e. they used the first type of measurement approach described above.

The second case study was a test of the method in the schematic design phase of a school building. However, the test was not completely put into "real life"; it was done using an actual building project as a case, but including only the architect from the actual design team. The other participants of the test did not participate in the actual building project. In this case study, the participants used predefined, linear measurement scales, i.e. the second type of measurement approach described above.

The third case study was a test of the method fully implemented in a real life building project. All the actual members of the real-life design team, including the client, participated in the test. In this case, the participants used the logarithmic type scales, i.e. the third type of measurement approach described above.

9 Case 1

9.1 Introduction

This case is an example of how a multi-criteria decision-making method may be used in the development of a solar facade for an office building. The approach was applied in the EU project ASICOM (Amorphous Silicon Photovoltaics in Commercial Buildings), where the aim was to develop solar facade solutions based on a-Si PV. This work was carried out before the concept of the MCDM framework presented in this thesis was fully developed. Nevertheless, the example serves to show how the MCDM framework may work in a product development case.

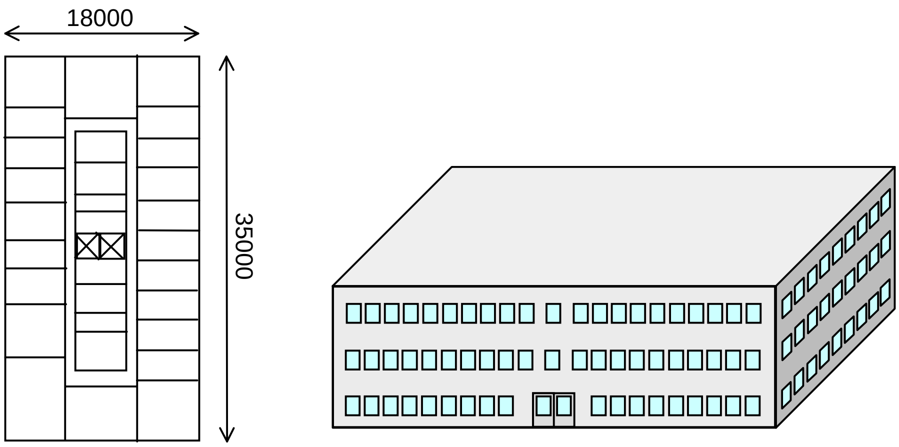
Design team

To represent the values and expertise of potential clients and designers in the European market place, a “model” design team was constructed. The design team consisted of scientists from the Norwegian University of Science and Technology, Faculty of Architecture. The scientists were playing the roles of an architect (Anne Gunnarshaug Lien, Ph.D. in architecture), an energy engineer (Inger Andresen, M.Sc. in building engineering), and a client (Anne Grete Hestnes, professor in architecture). The scientists possess considerable knowledge in solar energy design. In addition, the design team had the expertise of the rest of the ASICOM partners to draw on when designing the facade concepts. The design was based on the work that had previously been carried out within the ASICOM project.

9.2 Problem Formulation

Reference building

A generic type office building, relatively high standard, was chosen to represent a typical office building that would be a candidate for solar facade applications in Europe. The evaluations were done for 3 different locations that are representative for the range of European climates: Oslo – Norway, Würtzburg – Germany, and Nice – France.



Key numbers

Gross floor area	1890 m^2
Gross volume	5670 m^3
Number of floors	3
Area of exterior walls	954 m^2
Area of interior walls	1920 m^2
Window area	190 m^2
Number of parking spaces	20
Number of office work places	64

Occupation	8 am to 5 pm, Monday-Friday
Indoor air temperature	Temperature set point: minimum 22°C, maximum 26°C during occupied hours. Minimum 16°C, maximum 31°C during unoccupied hours.
Thermal insulation	Oslo, Norway: U = 0.22 W/m²K for wall, U= 0.15 W/m²K for floors and roofs Würtzburg, Germany: U = 0.5 W/m²K for wall, U= 0.3 W/m²K for floors and roofs Nice, France: U = 0.7 W/m²K for wall, U= 0.5 W/m²K for floors and roofs
Windows	bxh = 2x1m, placed in the middle of the façade of each cellular office, double pane insulating windows with aluminum frames. Oslo, Norway: $U_{glazing}$ = 1.5 W/m²K Würtzburg, Germany: $U_{glazing}$ = 1.8 W/m²K Nice, France: $U_{glazing}$ = 2.5 W/m²K Total solar energy transmittance = 0.61, Light transmittance =0.77. Automatic external venetian blinds (south windows only).
Ventilation	Air conditioning with cooling. Air volume 15 m^3/m^2h. Constant temperature and volume of supply air. Zoning. Heat recovery with 65% efficiency.
Heating	Water based radiators.
Cooling	Local cooling in computer centers. Cooling of ventilation air and local cooling ceilings.
Infiltration	0.2 ACH
Internal gains	Lights: 9 W/m², Equipment: 5 W/m², Persons: 4 W/m² (peak loads)
Exterior wall cladding	½-stone brick with special patterns.

9.3 Criteria Used

It was assumed that the typical European clients that would consider a solar facade for their buildings, would wish to emphasize low environmental loading, good indoor comfort, nice appearance, good functionality and good economics. Thus, the main criteria were:

- environmental loading
- comfort
- aesthetics
- functionality
- economics

The criteria were then described, and different possible ways to evaluate them were discussed. Then, the most appropriate level of evaluation was chosen for each criterion, and the background for these choices were documented. The description and discussion of the criteria were as follows:

Economy

Three different levels of doing an economic evaluation of a building project were discussed:

Level 1: Investment costs
Level 2: Life cycle costs
Level 3: “Total economic value”

Level 1 includes a consideration of the investment costs only. Until recently, this has been the most common procedure used as decision support for building investments in many European countries. The problem with this method is that it does not account for the future economic impacts of the project.

The method of Life Cycle Costs, LCC (level 2) is becoming more common. In addition to the initial construction costs, costs of physical operation over the useful life of the building are considered, see Figure 9-1. These include the costs of acquisition, maintenance, repair, replacement, and disposal. All costs are expressed as present value or other discounted value. There is an extensive literature on the use of LCC as a tool in the planning of buildings, including different methods for calculation and presentation of the cost-effectiveness of a project, see for example (Dell'Isola and Kirk 1981; Blom, Stenstad et al. 1988; Flanagan, Norman et al. 1989; Bejrum 1991; Mann 1992; Bjørberg, Eide et al. 1993; Bjørberg, Eide et al. 1993). The problem with the LCC method is that future costs of maintenance, replacement, etc., are hard to estimate. To deal with this, different methods for incorporating uncertainty and risk have been devised, see for example (Dell'Isola and Kirk 1981; Flanagan, Norman et al. 1989; Bejrum 1991; Mann 1992). Another problem is the determination of the rate of return, which very much influences the outcome of the calculation.

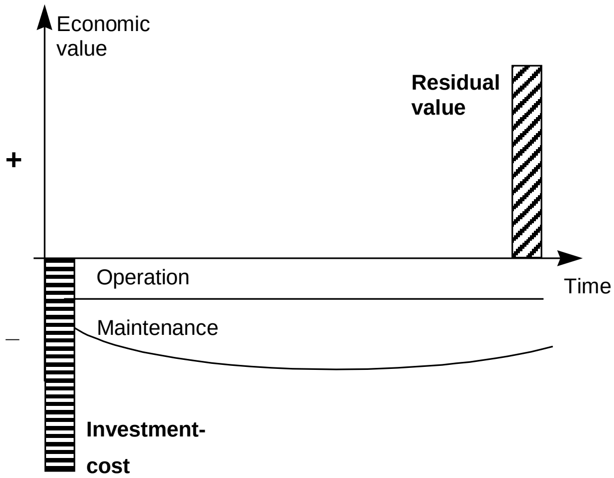


Figure 9-1. Illustration of the LCC model, adopted from (Bejrum 1991)

The level 3 economic criterion, “Total Economic Value”, is a concept that has just recently been introduced. It goes further than the life cycle costing in that it also includes more “hidden” building related costs or profits, like for example the productivity of the workers in the building (see for example (Andresen and Blakstad 1997)). This is an interesting view, due to the fact that over the building’s life cycle, the salaries of the building’s occupants dominate the costs of a company. A mere 1 percent increase in the productivity of the workforce produces savings that far outweigh annual operations and maintenance cost (including energy). The problem is that the relationship between the design of the building and the productivity of the workforce is very complex and hard to determine. Several case studies have been carried out to investigate the influence of different building related parameters such as indoor air quality, temperature, and daylight on the workers’ productivity (see (Williams and Oseland 1997) for a summary of recent research). However, the results are ambiguous, and there is a long way to go before we are able to do reliable estimations of this relationship during design.

For evaluating the economics of solar and other energy saving features of design, a concept based on the LCC approach is the most commonly used. Using investment costs alone will not show the future economic benefits of the fuel savings caused by the energy system. On the one hand the extra costs of providing the energy saving feature should be accounted for, and on the other hand the savings resulting from the lower energy use should be included. Thus, an energy-saving measure is worth while if:

$$C < B$$

where:

- C is the investment cost of the improvement plus the discounted future costs of maintenance, replacement and repair, and other quantifiable costs (e.g. loss of rentable space, increased cost of energy management).
- B is the discounted value of the future savings in fuel and any other quantifiable benefits (i.e. their net present value).

Still, there are the problems of estimating the future costs and benefits, estimating the expected lifetime of the system, and deciding the most appropriate rate of return. A common way of dealing with this, is to do a sensitivity analysis to check what happens to the conclusions when these parameters are varied within expected ranges.

Based on this discussion, the following recommendation was given:

Use a LCC approach including the marginal investment cost of the solar energy system plus the discounted value of the future maintenance, replacement and repair costs, plus the discounted value of the future fuel savings. Add a sensitivity analysis studying the effect of varying interest rates and fuel prices within expected ranges.

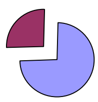
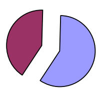
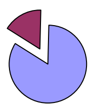
Table 9-1. Summary of the logic behind the choices regarding the economic criterion.

Possible representations	**Chosen representation**	**Why**
Investment cost	No	Does not account for the effect of the energy saved (as a consequence of the solar system) during the operation of the building.
Life cycle cost	Yes	Includes effect of marginal investment costs and future energy savings.
Total economic value	No	Too complicated and time consuming. Not sufficient data.

Environment

It is a well-established fact that buildings have a significant impact on the environment. Table 9-2 illustrates the comprehensive environmental effects of buildings.

Table 9-2. Environmental effects of buildings, (Roodman and Lenssen 1995).

Problem	**Buildings' share of problem**	**Effects**
Use of virgin minerals	40% of raw stone, gravel and sand. Comparable share of other processed materials such as steel. 	• Landscape destruction • Toxic runoff from mines and tailings • Deforestation • Air and water pollution
Use of virgin wood	25% for construction 	• Deforestation • Flooding • Siltation • Biological and cultural diversity losses
Use of energy resources	40% of total energy use 	• Local air pollution • Acid rain • Damming of rivers • Nuclear waste • Risk of global warming
Use of water	16% of total water withdrawals 	• Water pollution • Competes with agriculture and ecosystems for water
Production of waste	Comparable in industrial countries to municipal solid waste generation	• Landfill problems, such as leaching of heavy metals and water pollution

A complete environmental assessment of a building should include all life cycle phases of the building, from “cradle to grave or cradle”. The method of Life Cycle Assessment (LCA) has been internationally accepted through Society of Environmental Toxicology and Chemistry /SETAC, 1991/ and ISO 14000. The method includes an assessment of all environmental inputs and outputs of a process or a product of its life time, see Figure 9-2.

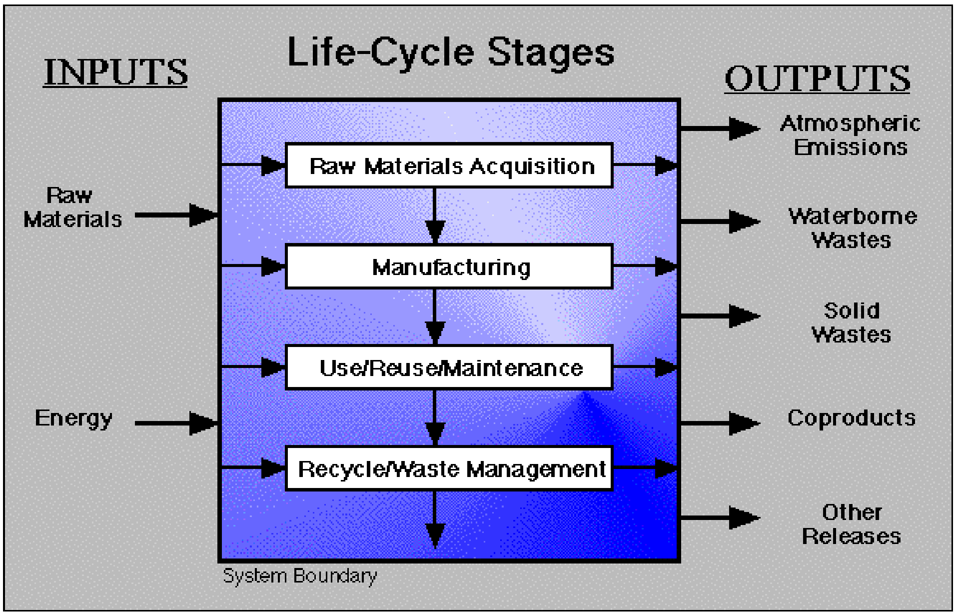


Figure 9-2. Life Cycle Assessment, (Lawrence Livermore Laboratory).

The main categories of environmental impacts are usually categorized into 3 main areas: resource depletion, human health, and ecological impacts, see Table 9-3.

Table 9-3. Main environmental impacts of a LCA, (Ministerråd 1994).

Impact Category	
Resource depletion	1. Resource depletion - energy and materials 2. Resource depletion – water 3. Resource depletion - land (including wetlands)
Human health	4. Human health - toxicological impacts 5. Human health - non-toxicological impacts 6. Human health impact in work environment
Ecological impacts	7. Global warming 8. Depletion of stratospheric ozone 9. Acidification 10. Eutrophication 11. Photo-oxidant formation 12. Ecotoxicolgical impacts 13. Habitat alteration and impacts on biological diversity

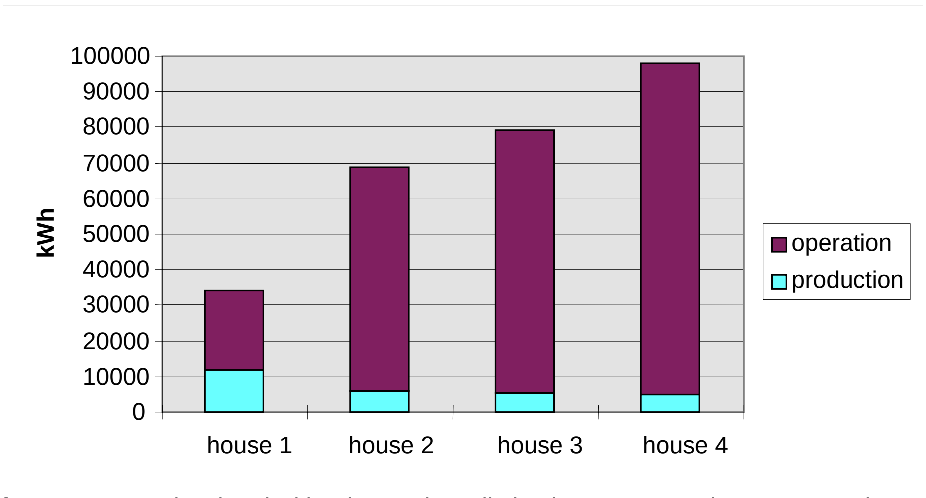
Due to the high degree of complexity, a complete life cycle analysis will be too time consuming in a standard building project. Therefore, it is necessary to concentrate the analysis on the most important issues. Unfortunately, it is not very easy to decide what are the most important issues. In the literature of environmental impact assessment, three helpful indicators are often mentioned to aid this assessment: *time*, *exposure*, and *magnitude*. *Time* refers the duration of the environmental impact, that is how long the impact will last. *Exposure* refers to the size of the geographic area and the number of people that will be affected. The *magnitude* refers to the severity of the impact. Often, also the probability of the occurrence and the reversibility of the effect are included.

For evaluating the environmental impact of solar energy systems in this case, it was decided to concentrate only on energy use. As was shown in Table 9-2, energy use in buildings is the source of very significant environmental effects. Therefore, an assessment of the energy performance of the building is probably the most important issue when comparing different energy saving measures. This does not mean that we should forget the other issues, such as waste minimization and toxic releases. Nevertheless, due to time limitations, energy performance was the only environmental criterion included here.

The energy performance may be assessed through three main life cycle stages:

- Energy for production of materials, products, systems, and building
- Energy for operation of the building
- Energy for demolishing of the building

Several studies (SBI 1990; Østergaard 1992; Myhre and Haugen 1993; Adalberth 1995; Fossdal 1995; Winther and Hestnes 1995; Winther 1998) have shown that the energy for operation accounts for the majority of the energy consumption, in the order of 90% of the total. However, if the amount of technical installations is very high, the energy for production should also be included in the assessment, see Figure 9-3.



house 1: super insulated with advanced ventilation heat recovery, heat pump and PV system.
house 2: well-insulated dwelling with ventilation heat recovery and solar thermal collectors.
house 3: well-insulated house with heat pump for space and water heating.
house 4: standard insulated house with no special energy saving measures.

Figure 9-3. Energy consumption for production and operation (50 years) of a row house unit with 4 different levels of energy efficient measures, (Winther and Hestnes 1995).

The energy consumption for operation may be separated into thermal and electrical energy, since these are associated with different environmental loadings. Thermal energy consumption consists of space and domestic hot water heating. The electrical energy consumption is composed of space cooling and electricity for fans, pumps, lights and appliances. These may be estimated using computer simulation programs, simple calculation tools, or rules of thumb.

Table 9-4. Summary of logic for the choice of representation of the environmental criterion.

Possible representations	Chosen representation	Why
Complete LCA	No	Too time consuming, sufficient data not available.
Energy consumption for construction and operation, separated into thermal and electric energy.	Yes	Probably the main environmental effect of solar systems is their effect on energy use for construction and operation. There is no other special characteristics of solar systems that significantly affects the environment differently than other building materials or systems.

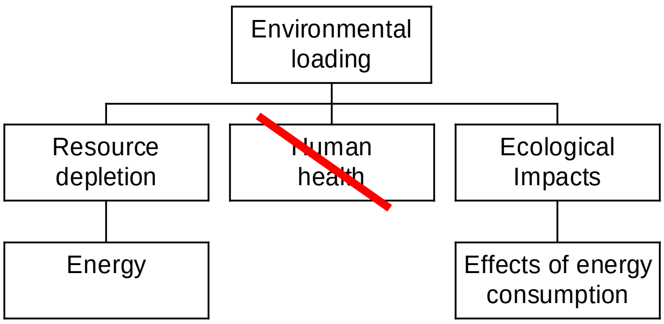


Figure 9-4. Hierarchical structure for the environmental criterion.

Aesthetics

Aesthetics can be defined as that which is concerned with the characteristics of objects and of the human being perceiving them that make the object pleasing to the senses *(U.S.Army 1989)*. However, numerous definitions of aesthetics exist, and there is no agreement among professionals or the public related to any one of these definitions. Furthermore, what is particularly pleasing in terms of aesthetic quality to one individual may not necessarily be pleasing to another. Reekie (Reekie 1972) suggests that there may be some way to handle the problem more objectively:

A distinction has to be made between the term "visually satisfactory" and the word "aesthetic". The latter should properly be used in regard to beauty – a special and intense visual quality. But beauty is subjective. What one person finds beautiful, another may find unattractive or ugly. Visual satisfaction results from the objective appreciation of the appearance of objects which are well-designed in accordance with generally accepted basic principles.

Reekie also specifies a number of visual design parameters (Reekie 1972):

- Light
- Color (harmony, contrast, psychological effects)
- Surfaces – texture, transparency, translucency, reflectivity, shadows, shade, pattern

- Form, shape and line
- Proportion

In a Ph.D. thesis, Westerman (Westerman 1980) identifies some common preferences with respect to visual evaluation. For examples, she shows that the sense of beauty is related to an optimal number of surfaces, edges and lines in the building facades.

For evaluating aesthetics of facades in this project, the term visually satisfactory as described by Reekie, was implied. The terms *scale/proportion* and *integrity/coherence* were used to describe the appearance of the different facade cases. *Scale and proportion* deal with the size and proportion of the elements themselves and the size, proportion, and placement of the elements relative to the size and proportion of the building. *Integrity and coherence* describe the overall appearance of a building with PV elements and the suitability of using PV-elements on special types of buildings. The meaning of these terms were illustrated in some examples (Andresen, A. G. Lien et al. 1999), but these will not be included here.

Functionality

The functionality of the building was defined as the PR-value (public relations value - what people like / dislike) and the flexibility. In this case, the PR-value for office buildings with a solar facade was to show “green thinking” and have a “hi-tech” expression, thus portraying the company occupying the building as caring about the environment and being technically advanced. Flexibility was set to include technical flexibility, energy flexibility and the possibility of interior flexibility.

Comfort

Comfort may be defined as the well being of the occupants of the building, and is usually organized into 5 main areas:

- Visual comfort
- Thermal comfort
- Atmospheric comfort (indoor air quality)
- Acoustical comfort
- Mechanical comfort (ergonomic, accidents, etc.)
- Psychosocial comfort

Properly designed, the solar energy system of a building will not have significant effects on the atmospheric comfort, the acoustical comfort and the mechanical comfort. However, visual and thermal comfort is very much influenced by the solar design, and must be accounted for. To some degree, the psychosocial comfort may also be influenced (for example may automatic controls of lights or shading devices reduce the users’ control over their environment, and the introduction of large glazing areas may reduce the users’ feeling of privacy). Thus, the concepts of thermal, visual and psychosocial comfort need to be included.

<u>Thermal Comfort</u>

Thermal comfort is undoubtedly a very subjective value. An environment that seems thermally comfortable to some people, may be totally unacceptable to others. Not only are people differently dressed and have different metabolic rates, their assessment of comfort is also influenced by their psychosocial environment.

No calculation method can predict exactly what will happen in a building under actual operating conditions. Important variables such as occupant density, shading, and equipment heat gain are dependent on factors that are more or less impossible to predict accurately. Sensitivity analyses may help to reveal the robustness of the building, but the amount of effort required is considerable.

Despite this, there are standards and so called "objective" methods for assessing thermal comfort quantitatively. The most common ones are ASHRAE standard 55-92 (ASHRAE 1992), ISO Standard 7730 (ISO 1984). Typically, six basic variables are used to describe the effect of thermal comfort:

- clothing level
- degree of activity
- air temperature
- radiant temperature
- air velocity
- relative humidity

Both standards are based on the concepts of PMV and PPD developed by P.O. Fanger (Fanger 1970). Based on laboratory experiments, Fanger has developed a correlation between parameters in the indoor environment and people's sensation of thermal comfort. This thermal index is called the "Predicted Mean Vote" (PMV) and is a function of activity, clothing, air temperature, mean radiant temperature, relative air velocity and air humidity. As a measure for the thermal sensation, the following psychosocial scale is used:

-3 = cold
-2 = cool
-1 = slightly cool
0 = neutral
+1 = slightly warm
+2 = warm
+3 = hot

The mathematical expression for PMV is rather complex, but tables and diagrams are available from which PMV can easily be determined. The "Predicted Percentage of Dissatisfied" (PPD) of a large group of persons is an indication of the number who will be inclined to complain about the environment. PPD is therefore suggested as a meaningful "figure of merit" for rating the thermal quality of a given indoor environment. The predicted percentage of dissatisfied, PPD, is related to the PMV as follows:

$$PPD = 100 - 95 \exp[-(0.03353\ PMV^4 + 0.2179\ PMV^2)]$$

Accepting that no single environment is judged satisfactory by everybody, the standards specify a comfort zone based on 90% acceptance or 10% dissatisfied. This criterion leads to an upper limit for operative temperature in summer of 26°C, given

50% relative humidity, sedentary activity, 0.5 clo and a mean air speed of less than 0.15 m/s.

The PMV model is interpreted as a constant set-point for a given clothing, metabolic rate and air velocity. It does not consider any effects due to adaptation, cultural differences, climate and seasons, age, sex or psychosocial attributes. Recent research casts doubt upon the application of steady-state heat exchange equations to what in practice is a variable environment (Clements-Croome 1997). People are not passive recipients of the environment, but take adaptive measures to secure thermal comfort. They may modify their clothing or activity, modify the lighting or solar heat gains, or modify the ventilation rate through opening of doors and windows. This suggests that a more "adaptable" method of comfort judgement is needed.

Thus, the evaluation of thermal comfort conditions at the design stage becomes a very complicated task. Advanced computer simulation programs may predict operative temperatures, temperature swings, relative humidities and air speeds in a building with "predictable" occupants. However, the behavior and adaptability of the future occupants is hard to predict. Therefore, putting a lot of effort into advanced simulation of thermal comfort may be useless. A more practical approach may be to make sure that the air temperature and the "cold draught" from windows stays within acceptable limits. Many thermal computer simulation codes offer the possibility to check the room temperature, or it could be checked by simple hand calculations for a cold and a warm day. The cold draught from windows can easily be evaluated through the use of diagrams such as the one shown in Figure 9-5.

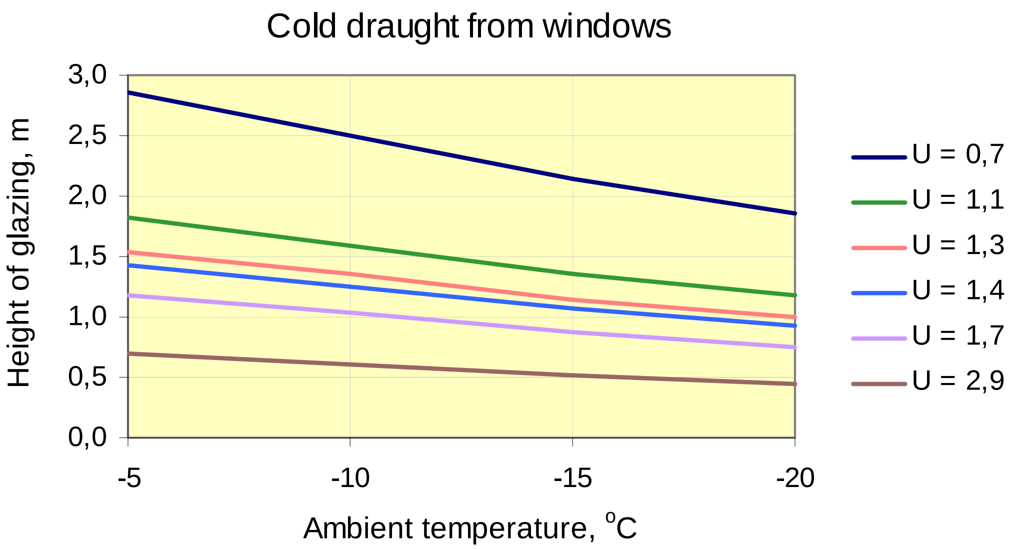


Figure 9-5. Maximum height of window that prevents unacceptable cold draft as a function of ambient temperature and window center U-value (W/m²K). (By courtesy of Marit Thyholt, SINTEF Civil and Environmental Engineering, Trondheim).

Visual Comfort

Visual comfort and ease of seeing are dependent on:

- illuminance level
- glare

- luminance distribution (brightness)
- color rendition
- object modeling

A minimum *illuminance level* is required for performing tasks that involves seeing. Table 9-5 shows an example of recommended minimum illuminance levels for different work tasks.

Table 9-5. Recommended illumination levels for different work tasks. Adopted from (Baker, Fanchiotti et al. 1993).

Work task	Illuminance (lux)
Office	500-750
Laboratory	500-750
Teaching, conference	300-500
Workshop	300-1500

Discomfort glare is the annoyance or pain caused by high luminances in a person's field of view. The degree of discomfort glare depends on the size, luminance and number and position of glare sources. Background luminance is also a factor.

The *luminance distribution* or brightness is determined by the relative amount of light available at the work surface in relation to the level of illumination in the field of view. The eyes function most comfortably and efficiently when the brightness relationships are not excessive.

For perfect *color rendition*, the light has to include all wavelengths and the reflectance of light of the respective wavelengths should correspond to the power of radiation of the same wavelengths. Only white light that consists of all wavelengths, such as sunlight, gives perfect color rendering of all possible colors.

The lighting in a room should be so that the three-dimensional shape of objects should be clearly readable. The readability of shape is mostly dependent on the ability of the lighting to describe the shape, i.e. *object modeling*.

Daylight also has special qualities that people find attractive. The human physiological sight is perfectly tuned for daylight. The maximum spectral sensitivity of the human eye matches the maximum spectral area of daylight. Also, the diurnal and annual variation of daylight plays an important role in the adjustment of the human biological clock and regulates the hormone balance. Some studies have even indicated a strong relationship between daylight availability and the health and productivity of working (see for example (Burge, Hedge et al. 1987), (Nicklas and Bailey 1996), (Jesch 1998), (Wilkins 1993), and (Williams and Oseland 1997)). Also, building codes often requires a minimum amount of daylight in occupied zones.

Thus, the visual comfort in a room is quite complex and difficult to assess at the design stage. Much of the assessment could be done using three-dimensional scale models in laboratories, but this is very expensive and time consuming. Exact visual comfort calculations are difficult to perform because they depend not only on the locations and brightness of light sources, but also on the apparent size (i.e. solid angle) of the light sources as seen from a particular viewpoint. There is one commercially available computer tool that offers the possibility of doing visual comfort assessment; RADIANCE. This tool can produce realistic 3D displays of various lighting scenarios and provide quantitative analysis for visual comfort evaluation. However, the program requires very skilled users, and it is quite time consuming to properly model even a relatively simply room configuration.

Thus, for the early design phase of most practical projects, we are left with simple hand calculations, sketching, and rules of thumb. Such design methods may for example be found in (Aschehoug and Arnesen 1998), (Baker, Fanchiotti et al. 1993), (Bell and Burt 1995), (Littlefair 1996), and (Løfberg 1987). Figure 9-6 shows an example of a simple diagram that may be used when evaluating how the window size influences the daylight factor in an office space.

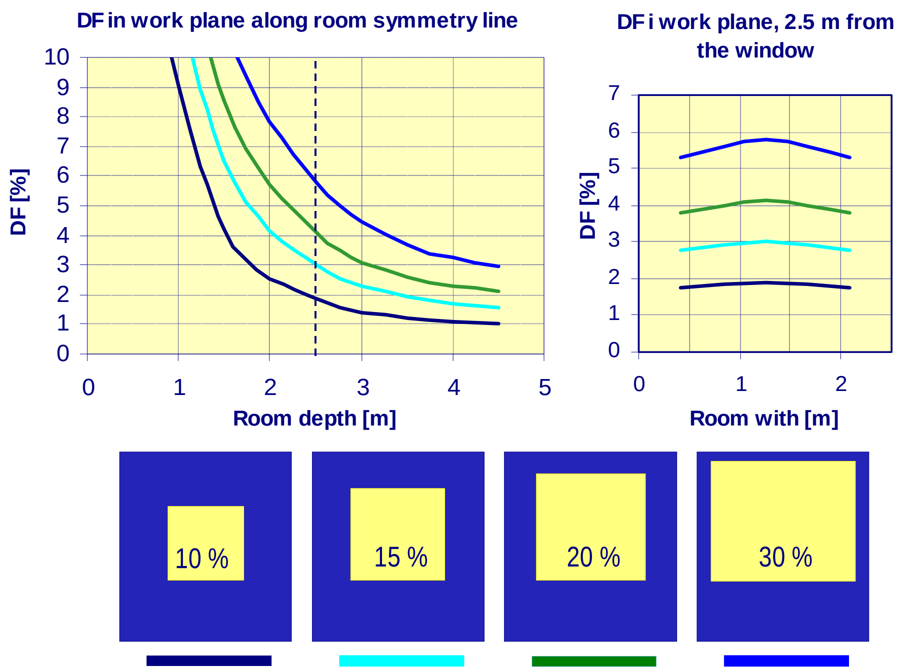


Figure 9-6. Daylight factor distribution in an office space as a function of window size, from (Aschehoug and Arnesen 1998).

Psychosocial comfort

Psychosocial comfort has to do with the relationship between people, communication, management, and the psychological impacts that the building environment has on people.

Building integrated solar energy systems may influence these relationships in various ways. The three most important factors may be:

- Individual control
- Privacy
- View

Several studies have indicated that there is a strong relationship between the degree of control over temperature, lighting and ventilation. The studies conclude that the well being and productivity of the workers increase when they are given the opportunity to control their own indoor environment (see for example (Burge, Hedge et al. 1987), (Abdou and Lorsch 1994), (Levin 1991), (Lorsch and Abdou 1994), (McCartney and Croome 1994), (Williams and Oseland 1997), and (Leaman 1997)).

Solar systems may involve large amounts of glazing – exterior and interior. This may diminish the feeling of privacy for the individual workers, unless some sort of screening possibilities are provided.

The opportunity to have some visual contact with the outdoor environment is generally regarded as a benefit to a person's well being. In fact, this issue is often mentioned in building codes, like for example in the British Standard Daylight Code: *"All occupants of a building should have the opportunity for the refreshment and relaxation afforded by a change of scene and focus"*.
Even though psychosocial comfort is very important, it was decided to leave it out of the study because it is very case-dependent, and it is therefore hard to generalize (given that the goal of the case study was to develop "generic" facade elements).

Figure 9-7 shows the hierarchy that summarizes the selection of sub-criteria for the comfort criterion. Tables 9-6 and 9-7 give summaries of the background for the choice of evaluation methods.

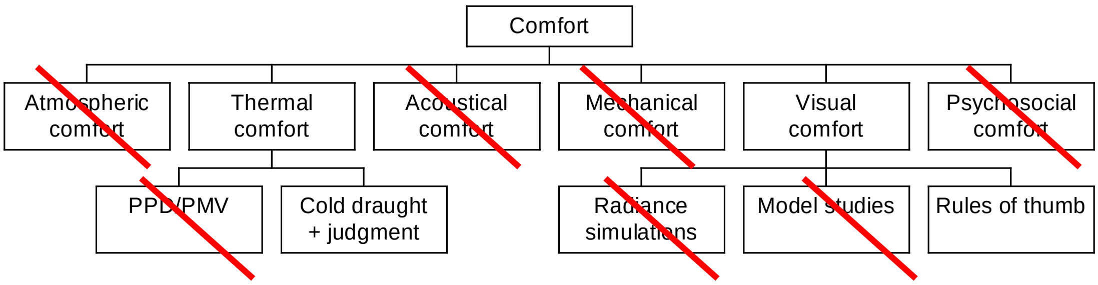


Figure 9-7. Hierarchical decomposition of the comfort criterion.

Table 9-6. Summary of background for representation of the thermal comfort sub-criterion.

Possible representations	Chosen representation	Why
PPD/PMV calculations	No	Too time consuming, sufficient data not available.
Estimation of cold draught from windows and an overall judgmental evaluation of the thermal comfort	Yes	

Table 9-7. Summary of background for representation of the visual comfort sub-criterion.

Possible representations	Chosen representation	Why
Radiance calculations	No	Too time consuming, sufficient data not available.
Model studies	No	Too time consuming
Rules of thumb and qualified judgements	Yes	

Summary

The resulting hierarchy of the chosen criteria for design and evaluation of the solar facades is shown in the figure below:

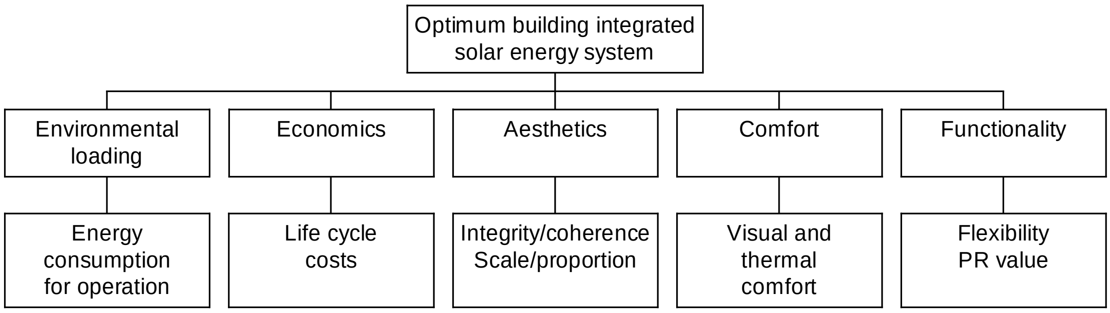


Figure 9-8. Hierarchy of criteria for solar facades.

9.4 Generation of alternatives

The different solar energy system types were structured in groups according to their use and technical characteristics, as shown in the following figure:

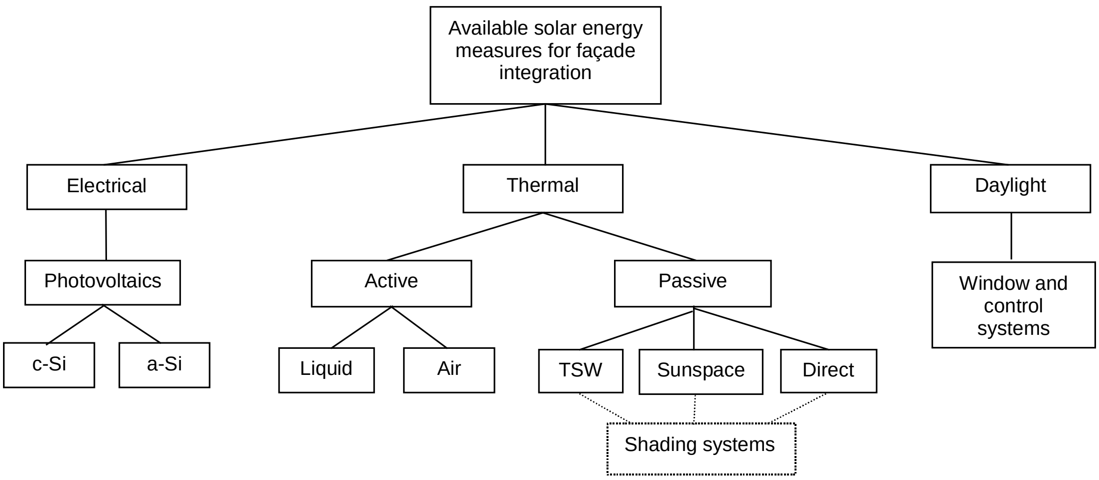
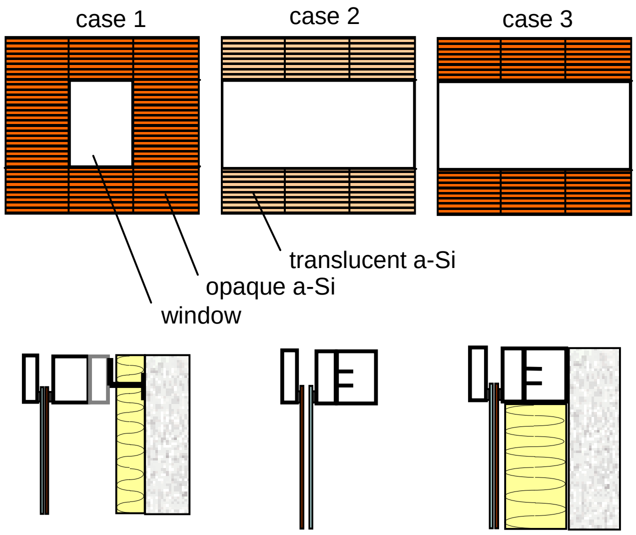


Figure 9-9. Solar energy technologies for building integration, structured hierarchically.

Based on an evaluation of the possible solar strategies, it was decided to concentrate on three main types of solar facade options for office buildings:

1. A-Si cladding. Amorphous silicon photovoltaic cladding elements with aluminum framing. Efficiency 4%.
2. C-Si cladding. Multi-crystalline silicon photovoltaic cladding elements with aluminum framing. Efficiency 12%.
3. Thermal collector cladding. Low efficiency air-collectors for space and water heating. $F_R U_L = 5.0$, $F_R(\tau\alpha) = 0.5$.

Based on the developments and evaluations that had been carried out within the ASICOM project, the following 3 facade configurations were chosen for further evaluation:



Case 1: Opaque solar cladding elements are compared to a reference cladding of natural stone. The solar cladding elements are: a-Si elements (developed in the ASICOM project), c-Si elements, and thermal collector elements. The c-Si and thermal collector elements are assumed to be comparable in standard to the ASICOM a-Si elements.
Case 2: Translucent solar glazing elements are compared to a reference glazing of colored glass (of the same translucency). The solar glazing elements include a-Si elements (developed in the ASICOM project), and similar mosaic crystalline-Si elements.
Case 3: Opaque solar cladding elements are compared to a reference of colored glass cladding. The solar cladding elements are: a-Si elements (developed in the ASICOM project), crystalline silicon elements, and thermal collector elements.

9.5 Performance Prediction

Performance prediction with respect to environmental loading, comfort, economics, aesthetics and functionality was carried out by the team. For the PV systems, the energy output was simply estimated based on the panel efficiency and yearly insolation on the facade, assuming grid-connected systems and electricity buy price equal to the sell price. For the thermal collector systems, the F-CHART method (Klein and Beckman, 1992) was used.

Performance Scales

Performance scales ranging from –1 to 2 were constructed for each of the criteria, as shown in the table below. The performances of the alternative facade claddings were then measured on these scales. For example, a solar facade layout that is judged to have “good” functionality (compared to the reference facade), is given a score of 1 on this criterion. Similarly, if the building with the solar facade consumes 10% less energy than the reference building, it receives a score of 1 on the environmental criterion.

Table 9-8. Performance scales for the criteria.

score:	-1	0	1	2
comfort	bad	as reference (neutral)	good	very good
functionality	bad	as reference (neutral)	good	very good
aesthetics	bad	as reference (neutral)	good	very good
economy	10% increase in LCC	as reference (neutral)	10% reduction in the LCC	20% reduction in LCC
environment	10% increase in energy use	as reference (neutral)	10% reduction in the energy use	20% reduction in the energy use

The performance prediction for facade type 1 is given below.

The reference facade has natural stone cladding. This is replaced by solar panels on the south facade. Figure 9-10 shows the layout of the facade of one office module with a cladding of solar panels. The active PV cell area / active solar collector area is 5.57 m² per office module, which gives a total of 184 m^2 for the south facade.

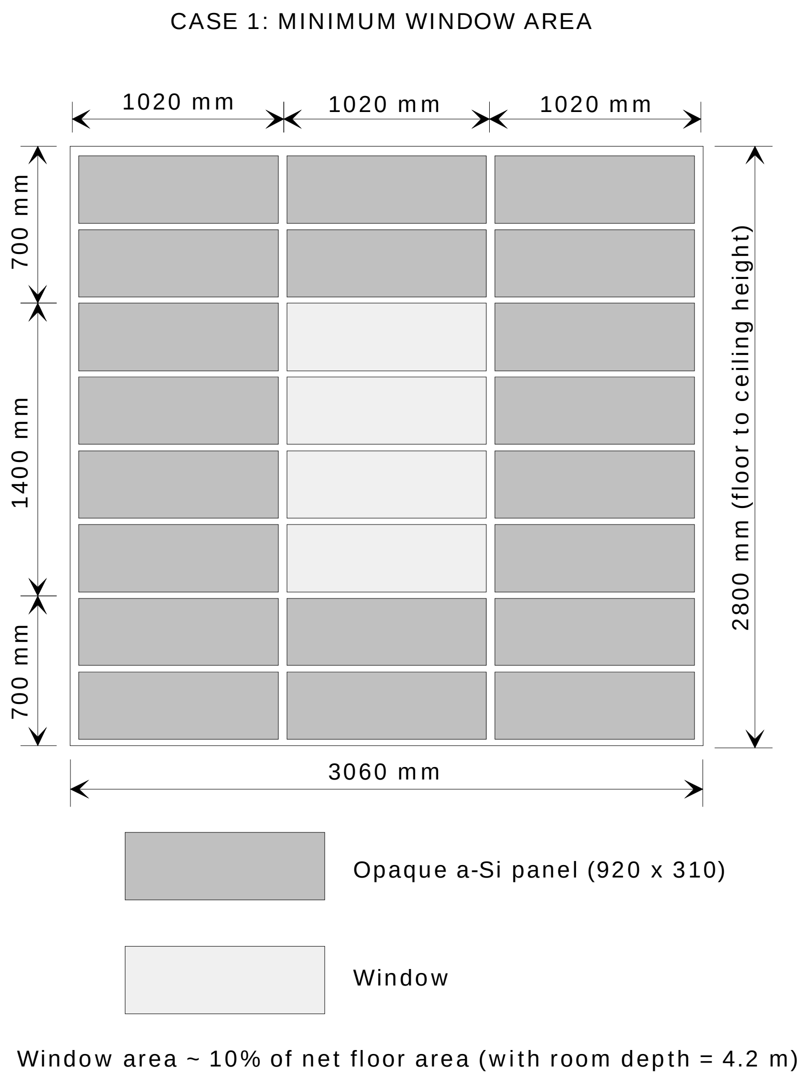


Figure 9-10. Office module facade layout, case 1.

Comfort

Changing the facade cladding will give no significant impact on the thermal or visual comfort in the room. Therefore, a score of “neutral” (0) is assigned to all the alternatives.

Aesthetics and Functionality

a-Si PV-facade

With respect to scale and proportion the aesthetics of this facade is evaluated as negative because the window area is limited and the possibilities for different designs of the facade are therefore also limited. The windows have to be located in similar positions for every office, and this facade type will therefore always appear as a surface with small holes in it. With respect to integrity and coherence this facade is also evaluated as negative. This facade type, with small holes in a large wall gives the impression of being a heavy building. The reference case with stone facade elements therefore has a more logical appearance. Seen from the inside of the room there will be no difference between case 1 and the reference case. Both cases have cladding on an opaque wall and the appearance of the interior is evaluated as neutral. The conclusion is that a-Si PV-facades used on case 1 scores "bad" (-1) on aesthetics.

The functionality (PR-value and flexibility) for this case is evaluated as positive although cases 2 and 3 fit better to the "green thinking and modern hi-tech appearance" image than case 1. This image is important also for case 1. Flexibility includes technical flexibility, energy flexibility and the possibility of interior flexibility. The technical flexibility is not as good for the PV-facades as for a conventional facade because of the complications of needed wiring. Interior flexibility is neutral and energy flexibility is a little positive for buildings with PV. The conclusion for PR-value and flexibility together is that case 1 scores "good" (+1) on functionality.

c-Si PV-facade

With respect to the integrity of this type of "heavy facade" the metallic look of the c-Si elements is evaluated as a little better than the a-Si elements. The conclusion is that c-Si PV-facades used on case 1 is not quite as attractive as the reference case and scores "bad to neutral" (–0.3).

The functionality is evaluated as a little better than "good to very good" (1.2) because of the hi-tech image of these elements.

Thermal collectors

Thermal collectors will have an appearance that is very much similar to a-Si PV-elements and the appearance is evaluated as the same for these two facade types. The score is "bad" (-1) on aesthetics.

The technical flexibility of a building with ducts in the facade is not good. Energy flexibility for thermal heat is not very important for office buildings. The PR-value for a high quality solar collector is quite good, though. The conclusion for PR-value and flexibility together is that case 1 scores "bad" (-1) on functionality.

Table 9-9. Scores for the Aesthetics and Functionality criteria.

	aesthetics	functionality (flexibility and PR-value)
a-Si PV-facade	- 1	+ 1
c-Si PV-facade	- 0.3	+ 1.2
thermal collectors	- 1	- 1

Environmental Performance

The total yearly heating and cooling energy consumption of the reference building was calculated using the computer program *Energy-10* (Balcomb et al., 1998) and climatic data for the three locations (Table 9-10). The energy production of the solar facades was estimated (Table 9-11) using simple calculation tools and compared to the total, climate dependent energy consumption of the building (Table 9-12). The embodied energy of the solar facades was accounted for. These numbers where then transformed to scores on the environmental criterion (Table 9-13).

Table 9-10. Energy performance for reference building

ENERGY (kWh/yr/m² gross floor area)	Oslo	Würtzburg	Nice
Heating energy consumption	-21	-19	-6
Cooling energy consumption	-7	-6	-13
Lighting energy consumption	-27	-27	-27
Total	*-55*	*-52*	*-46*

Table 9-11. Energy production of solar facades

ENERGY (kWh/yr/m² gross floor area)	Oslo	Würtzburg	Nice
a-Si PV facade	+4	+3	+5
c-Si PV facade	+11	+10	+15
thermal collector facade	+6	+5	+10

Table 9-12. Energy performance of the solar facades

The ratio of the energy production of the solar facade to the total energy consumption of the building	Oslo	Würtzburg	Nice
a-Si PV facade	7%	6%	11%
c-Si PV facade	20%	19%	33%
thermal collector facade	11%	10%	22%

Table 9-13. Environmental score of the solar facades

ENERGY (kWh/yr/m² gross floor area)	Oslo	Würtzburg	Nice
a-Si PV facade	+0.7	+0.6	+1.1
c-Si PV facade	+2.0	+1.9	+3.3
thermal collector facade	+1.1	+1.0	+2.2

Economic Performance

In calculating the life cycle cost (LCC) savings, an energy price (p) of 0.15 EURO/kWh was used for the electricity from the PV systems (buy price equal to sell price), and a price of 0.06 EURO/kWh was used for the energy from the thermal collector systems. The interest rate was fixed at 6% and the economic life time was set to 30 years.

Table 9-14. Economic performance of ASCICOM a-Si facade compared to reference (natural stone)

ECONOMY	Oslo	Würtzburg	Nice
Added investment cost	-50 EURO/m² * 0.4% of total cost **	-50 EURO/m² * 0.4% of total cost **	-50 EURO/m² * 0.4% of total cost **
Added O&M costs (per year)	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost
Energy savings (p = 0.15 EURO/kWh)	1130 EURO/yr	850 EURO/yr	1420 EURO/yr
Total LCC savings r=6%, p = 0.15	+24600 EURO +0.6 % of total LCC	+23000 EURO +0.5 % of total LCC	+28700 EURO +0.7 % of total LCC

* Investment cost of a-Si facade relative to natural stone facade. Total facade area covered with a-Si elements is 240 m² (about 80% of the south facade).
** 240 m² (area of PV facade, south facade only) x 50 EURO/m² divided by total investment for building (3,160,000 EURO)

Table 9-15. Economic performance of crystalline Si facade compared to reference (natural stone).

ECONOMY	Oslo	Würtzburg	Nice
Added investment cost	200 EURO/m² * 1% of total cost **	200 EURO/m² * 1% of total cost **	200 EURO/m² * 1% of total cost **
Added O&M costs (per year)	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost
Energy savings p = 0.15 EURO/kWh	3120 EURO/yr	2840 EURO/yr	4250 EURO/yr
Total LCC savings r=6%, p = 0.15	-7060 EURO -0.2 % of total LCC	-10900 EURO -0.3 % of total LCC	+8550 EURO +0.2 % of total LCC

* Investment cost of c-Si facade relative to natural stone facade. Total facade area covered with c-Si is 240 m² (about 80% of the south facade).
** 240 m² (area of PV facade, south facade only) x 200 EURO/m² divided by total investment for building (3,160,000 EURO)

Table 9-16. Economic performance of thermal collector facade compared to reference (natural stone)

ECONOMY	Oslo	Würtzburg	Nice
Added investment cost	250 EURO/m² * 2% of total cost **	250 EURO/m² * 2% of total cost **	250 EURO/m² * 2% of total cost **
Added O&M costs (per year)	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost	0.6 EURO/m² 0.2 % of total O&M cost
Energy savings p = 0.06 EURO/kWh p = 0.2 EURO/kWh	670 EURO/yr 2200 EURO/yr	716 EURO/yr 2400 EURO/yr	1100 EURO/yr 3700 EURO/yr
Total LCC savings r=6%, p = 0.06 r=6%, p = 0.2	-53000 EURO -1.2 % of total LCC -31000 EURO -0.7 % of total LCC	-52000 EURO -1.2 % of total LCC -29000 EURO -0.7 % of total LCC	-47000 EURO -1.1 % of total LCC -11000EURO -0.3 % of total LCC

* Investment cost of thermal collector facade (650 EURO/m²) relative to natural stone facade (400 EURO/m²). Total facade area covered with thermal collector facade is 240 m² (about 80% of the south facade). ** 240 m² (area of PV facade, south facade only) x 250 EURO/m² divided by total investment for building (3,160,000 EURO)

Table 9-17. Economic score of the solar facades

ENERGY (kWh/yr/m² gross floor area)	Oslo	Würtzburg	Nice
a-Si PV facade	+0.06	+0.05	+0.07
c-Si PV facade	-0.02	-0.03	+0.02
thermal collector facade	-0.12	-0.12	-0.11

Similar assessments were carried out for alternatives 2 and 3, see (Andresen, A. G. Lien et al. 1999) for a detailed description. The scores for the different alternatives were presented in "star diagrams". A star diagram show an overall picture of how well the facades score on the different criteria (with equal weights on all criteria). The center of the star will represent the lowest point on the scale, i.e. the worst score (-1). Thus, the better the score, the more of the star will be filled, or shaded. For example, the reference building which has a score of "0" on all criteria, will have a star diagram as shown in Figure 9-11 (shaded area). A very good building will cover the whole area of the star.

Only the star diagrams for the solar facades on buildings located in Oslo are shown here, Figure 9-12.

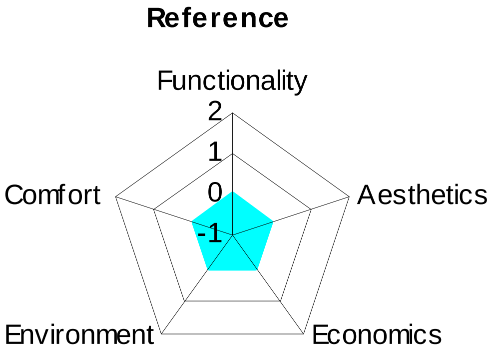


Figure 9-11. Star diagram for the reference building.

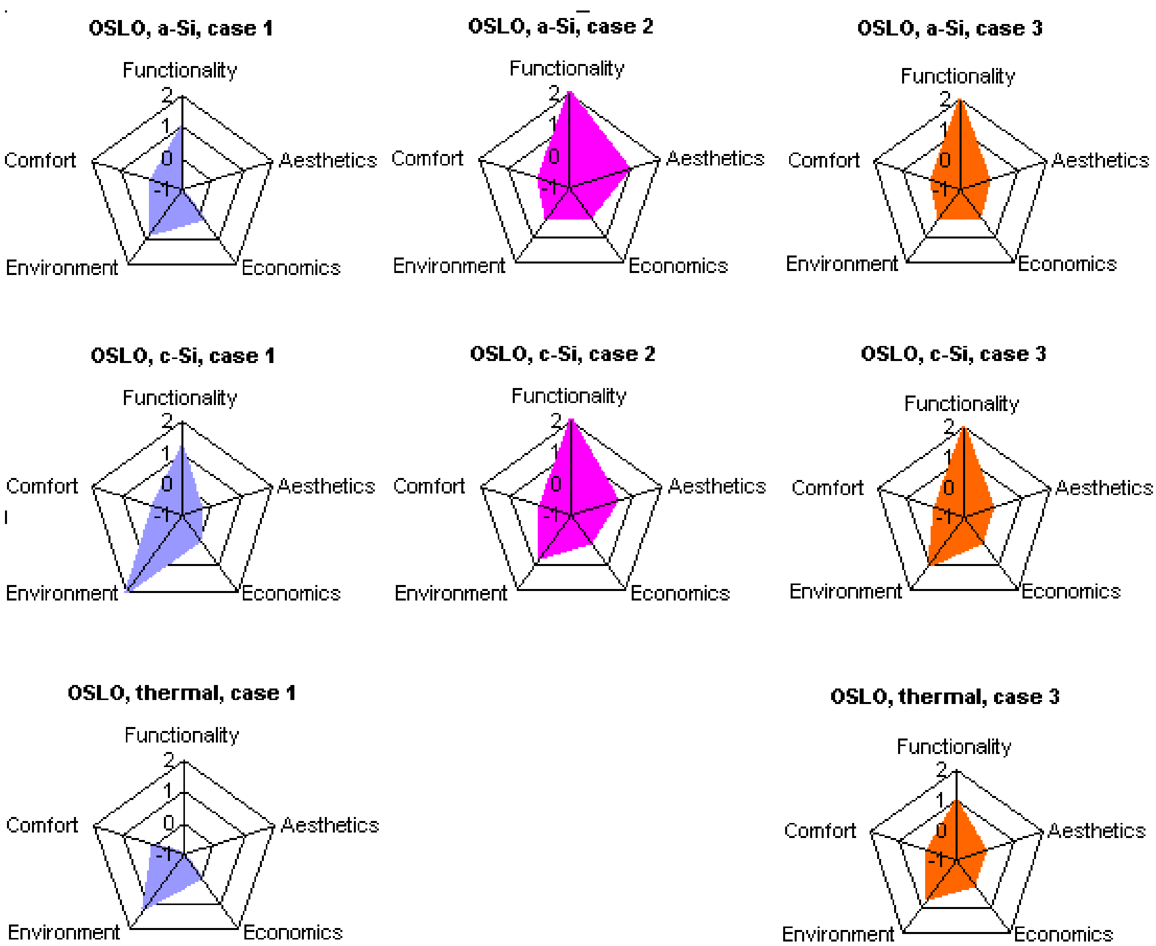


Figure 9-12. Star diagrams showing the score for the different facade options for the office located in Oslo (the star diagram in the middle of the lower row is not shown because a thermal facade is not feasible for type 2 layout.

Based on the above star-diagrams, the following preliminary findings were stated:

- Case 1 with a c-Si facade scores the highest on the environmental criterion. This is because case 1 has a large area for energy production.

- The thermal facades have low scores on functionality. Case 2 and 3 score better on the functionality criterion than case 1.

- Case 1 has a low score on aesthetics for all the solar facade options.

- There are almost no differences between the facade options with respect to the economic score.

9.6 Evaluation

The team weighted the criteria in two different ways:

1. A direct ranking of the criteria starting with the most important criterion which was given a weight of 1.0. The remaining criteria were assigned weights between 0 and 1 according to their relative weights.
2. A ranking using a trade-off analysis as described in chapter 6 (Figure 6-20).

The two methods produced different outcomes, as illustrated in Figure 9-13.

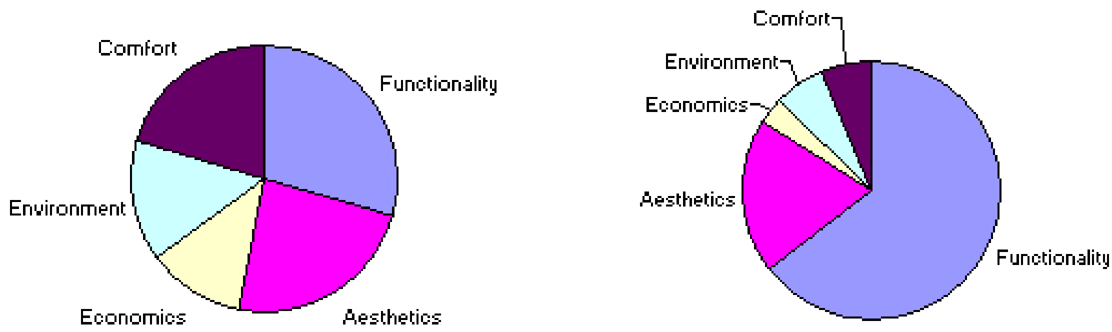


Figure 9-13. Results of weightings. Direct weighting to the left, weighting through trade-off analysis to the right. The larger the size of the pie slice, the higher weight.

The scores on the different criteria were multiplied by the respective weights and added into an overall score for each facade solution:

$$S = \sum_i weight_i \times score_i$$

where i represent the criteria (environment, economics, comfort, aesthetics, functionality).

The overall scores for the two different weighting methods are shown in Figure 9-14.

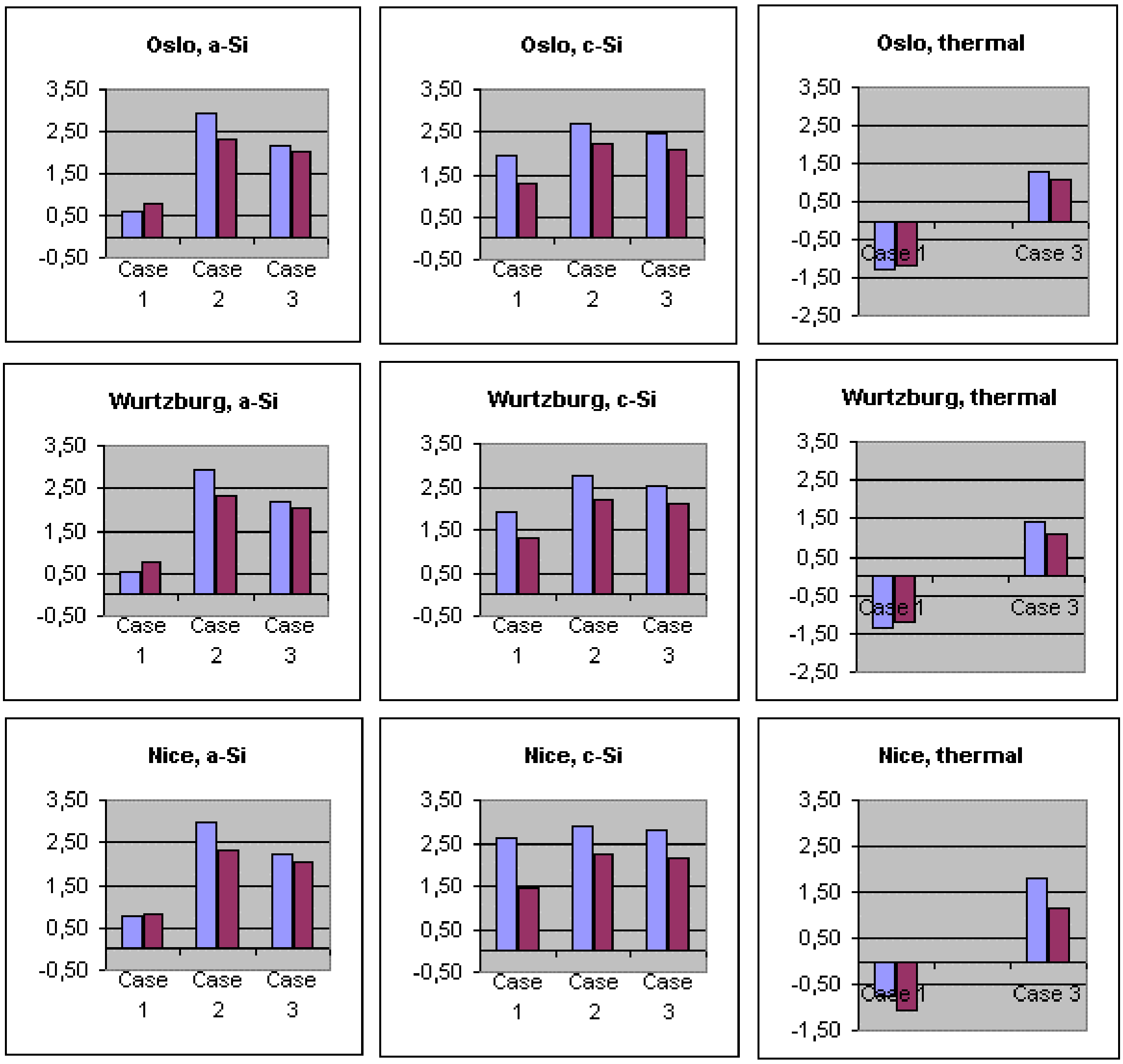


Figure 9-14. Total weighted scores. The bars to the left are based on the direct weighting method, the bars to the right are based on weighting through trade-off analysis.

Looking at the figure above and the star diagrams, the following preliminary conclusions were drawn:

Case1: The c-Si PV facade receives the highest score. It has superior score on the environmental and the aesthetic criteria.

Case 2: The a-Si PV facade receives the highest score, closely followed by the c-Si facade. This is mainly because the a-Si facade scores better on aesthetics, which has a relatively high weight.

Case3: The c-Si PV facade receives the highest overall score, closely followed by the a-Si PV facade. This is because it scores better on the environmental criterion.

Overall: Case 2 with the a-Si facade receives the highest overall score. In general, the thermal collector facades do not compete because they score low on functionality.

These conclusions hold for all the locations. In general, all the solar facades score better in Nice, because of higher energy production at the lower latitude. This is especially the case for the thermal collectors.

9.7 Sensitivity Analysis

During the process, the design team gained greater understanding of what the different design criteria really meant. They realized that what they had assigned to the criterion *functionality* when weighting the criteria, might not be the same as what they later meant by functionality. When weighting, they thought of functionality as the functionality of the whole building. Later when they scored the alternatives with respect to functionality, they limited this to include PR value for the facade (as seen from the outside) and flexibility of the facade with respect to energy and a kind of "ease of change" with respect to exterior and interior layout. Then, the design team realized that they might have assigned a too high weight to the functionality criterion. This led them to the conclusion that the direct weights were probably the ones that most closely reflected their values.

They went back to have a look at the star diagrams to study the scores for each criterion with no weighting applied. The star diagrams showed that the scores on the economic criterion were almost the same for all alternatives. This was due to the fact that the performance scale ranged from –10% to +20% change in the LCC, while all the alternatives stayed within –1.2% to +0.7% of the total LCC. The design team realized this, and agreed to do a sensitivity study with an "enlarged" economic performance scale as follows:

score:	-1	0	1	2
economy	1% increase in LCC	as reference (neutral)	1% reduction in the LCC	2% reduction in LCC

The new star diagrams and total scores are shown for Oslo only, Figure 9-15. There are now visible differences in the economic performances. The a-Si facades score the highest on the economic criterion, and this is valid for all facade configurations. On this criterion, the a-Si facades score relatively higher than the competing solar facades for the higher latitudes (Oslo and Würtzburg).

The "enlarged" economic scale implied that the corresponding economic weight factor should be reduced, if the overall evaluation should still be the same. However, the team felt that they had put far too little weight on the economics. Therefore, they decided to test this new economic scale with the same weight factor as in the original assessment, thereby, in effect, increasing the weight on the economic criterion by a factor of 10 compared to the first assessment.

Figure 9-16 shows that there is little change in the main conclusions. The a-Si PV facade still has the highest score for Case 2, the distance down to the c-Si facade is now a little bit larger. For Case 1, the c-Si PV facade is still slightly superior, though the distance to the a-Si is somewhat smaller. And the thermal facades still don't compete with the PV facades for all cases and locations.

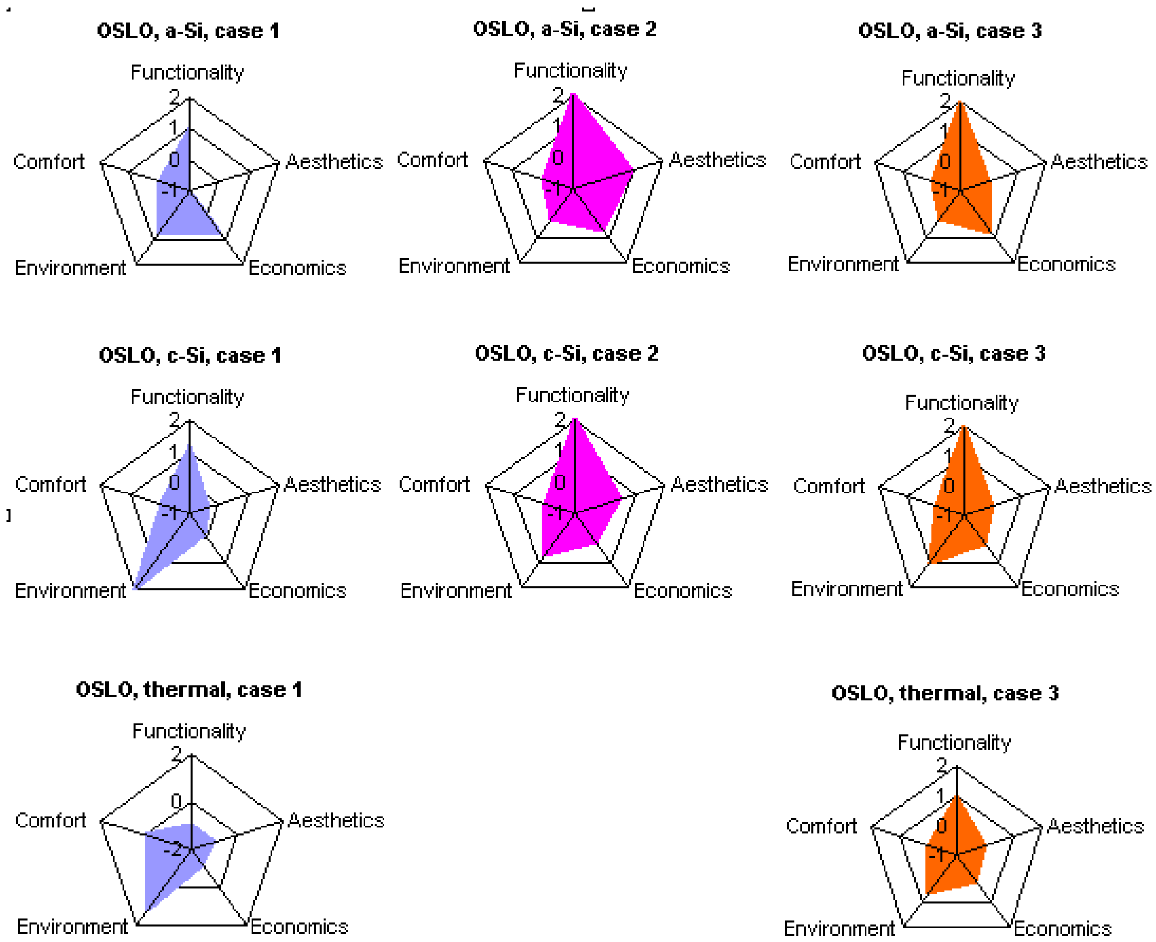


Figure 9-15. Star diagrams for the solar facades located in Oslo, "enlarged" economic scale.

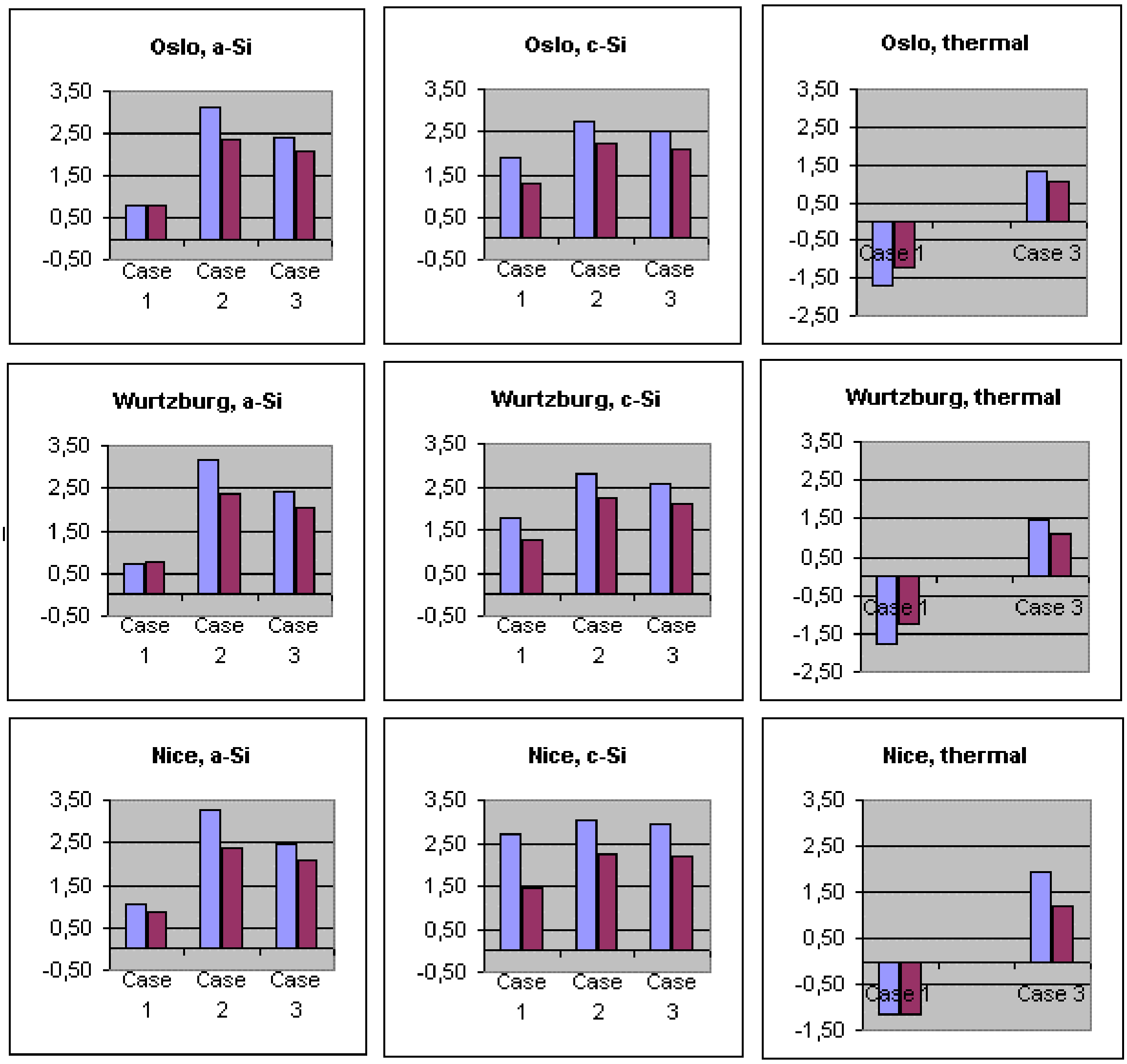


Figure 9-16. Total weighted scores with "enlarged" economic scale. The bars to the left are based on the direct weighting method, the bars to the right are based on weighting through trade-off analysis.

9.8 Lessons Learned

The design team found that the hierarchical way of structuring the criteria was a useful tool to help see the whole picture, while at the same time focusing on what is most important. It was also helpful in finding the right level of detail in which to do the evaluations of the criteria (i.e. the balance between criteria).

The team had some problems finding appropriate scales for the criteria. The economic scale was first chosen so wide that it did not discriminate between the alternatives. The reason for this might be that it is hard to generalize economics, and thus the team had problems finding a generic value system for this criterion.

The star diagrams were found to be valuable in comparing individual attribute performances across alternatives. However, the team realized that they could not be used to compare overall performances unless the weights were equal.

The team had some trouble determining the proper weights. This was due to the fact that they were to express preferences of a "generic solar building market". This was just based on the experience or "gut feeling" of the team members. A market survey might have made the task less ambiguous. The team also felt the need for a formalized and simple way of connecting the weights to the scales.

In general, the team felt that the approach was a useful way to document the conclusions of the evaluations. Even though they had some a priori feeling about what solutions would be more feasible, they felt more comfortable that the best solution was found when using this structured approach. They also found that the method brought up interesting discussions about issues that might otherwise have been overlooked. Furthermore, the team members felt that they had gained a deeper understanding of each other's fields of expertise, e.g. the architect learned more about energy engineering issues, and the energy engineer learned more about architecture.

10 Case 2

10.1 Introduction

This case was a test of the (preliminary) MCDM approach that was conducted during a meeting in Oslo, June 24, 1999 (09:30-15:30). The test was partly theoretical and partly practical. It was practical in that it was conducted on a real building project that the architect (Per Monsen) was currently working on. It was theoretical in that the other members of the test group were playing the roles of the “real” members of the design team.

The design team consisted of the following:

- Anne Grete Hestnes, Professor at the Department of Building Technology, Norwegian University of Science and Technology, Trondheim. Playing the role of the representative of the client.
- Per Monsen, architect with *GASA Architectural Office A/S*, Oslo. The architect of the building project.
- Ida Bryn, HVAC engineer at the HVAC consultant *Erichsen and Horgen A/S*, Oslo. Playing the role of the HVAC engineer of the project.
- Inger Andresen, Ph.D. student at the Department of Building Technology, Norwegian University of Science and Technology, Trondheim. Process leader.

10.2 The Process

The process leader suggested a 7- step procedure for the test:

1. Presentation of the case project by the architect.
2. Description, structuring, and selection of design objectives (criteria), including a preliminary weighting.
3. Generation of alternative solutions.
4. Performance prediction.
5. Weighting of criteria.
6. Aggregation.
7. Sensitivity analysis.

This procedure was accepted.

1. Presentation of the case project.

Per Monsen presented the case project. The project is a school located at Søndre Nordstrand, near Oslo. At the time of the meeting, the schematic design had been carried out. The building has a net floor area of 10000 m². Floor plans and sections are shown in Figures 10-1 to 10-3.

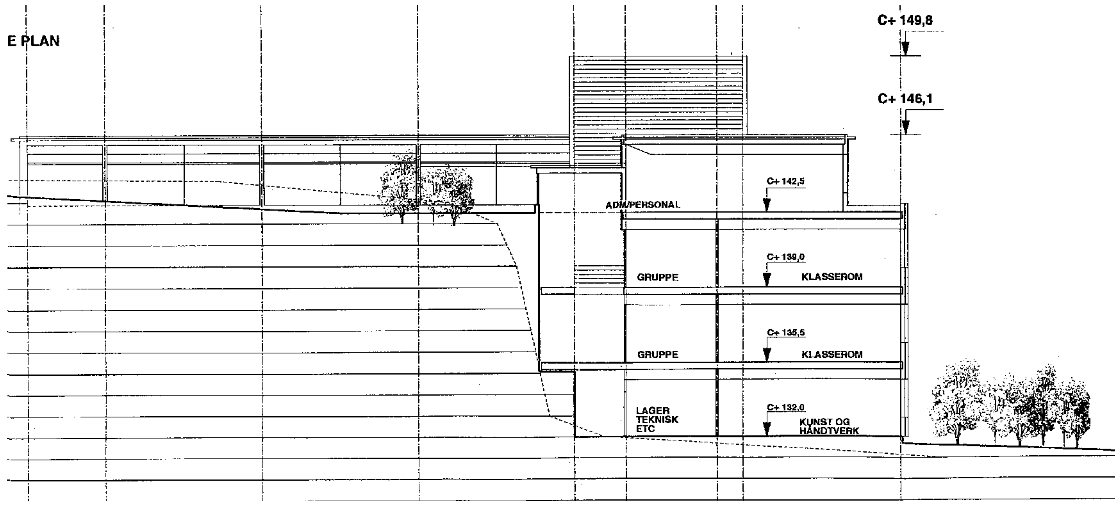


Figure 10-1. Vertical cross-section.

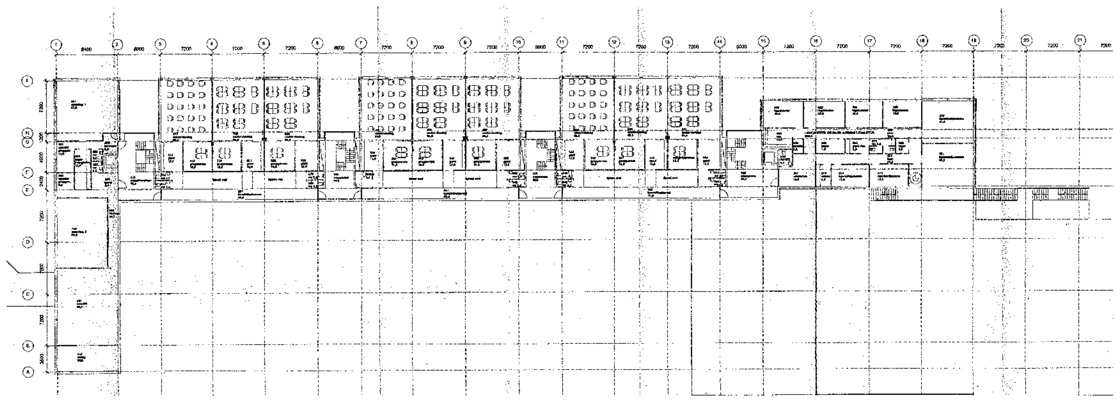


Figure 10-2. Horizontal cross-section showing the 3rd floor.

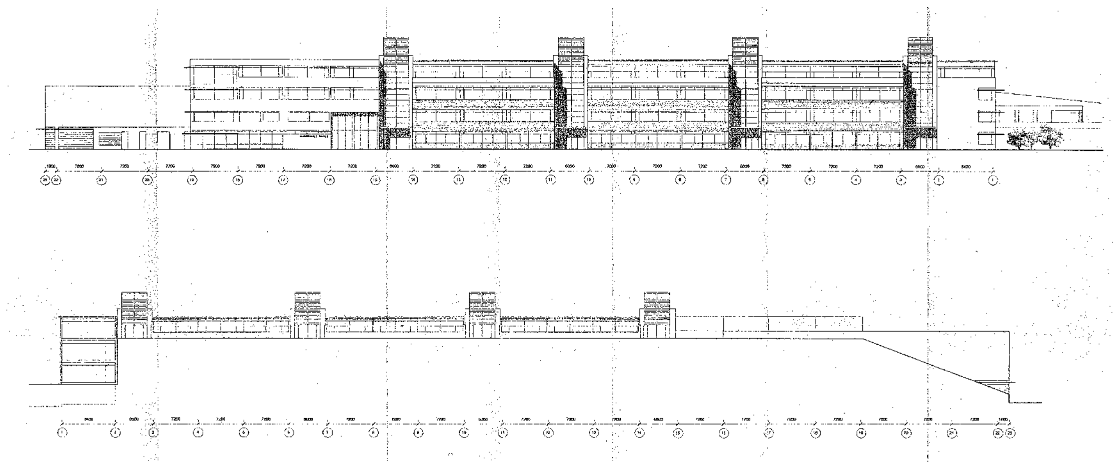


Figure 10-3. Facades facing north-east (top) and south-west (bottom).

The proposed schematic design was chosen as the reference case for the MCDM test. This building is specified according to the current building code, and has no special solar or low-energy features.

The building has been partially integrated into the steep hill to reduce the facade area and to avoid overheating problems. The main facade is facing north-east. This allows for good daylight conditions while reducing overheating and glare problems due to direct solar insolation. Daylight may also enter into the corridors and group rooms at the 1st and 2nd floors through the north facing windows at the 3rd floor (Figure 10-1). The school is designed to meet the new educational specifications in Norway; the 60 m² classrooms are connected to the 30 m² group rooms. Wardrobes are located in the group rooms.

There are 4 ventilation rooms, each serving the accompanying section of the building. This allows for only vertical ductwork through the four vertical shafts, 5 stories high.

2. Description, structuring and selection of design objectives (criteria)

The design team discussed the criteria proposed for IEA Task 23 (Table 10-1). They decided to use only the total life cycle cost as the economic criterion, instead of splitting it into construction, operating and maintenance costs. For resource use, they decided only to include electricity and fuel consumption, and disregard the other sub-criteria. This was because data on water, land and materials consumption was impossible to obtain during their limited time. The team also decided to drop the Environmental Loading criterion. Since the gas emissions listed below this criterion are mainly connected to energy use, they argued that this could be accounted for in the Resource Use criterion. For the remaining criteria (Architectural Quality, Indoor Quality, and Functionality), they decided to keep them as proposed by Task 23. The design team concluded that in this way, the most important criteria had been included.

Table 10-1. The IEA Task 23 Criteria.

Criteria	Sub-criteria
Life-Cycle Cost	Added construction cost
	Annual operating cost *
	Annual maintainance cost
Resource Use	Annual electricity *
	Annual fuel *
	Annual water
	Construction materials
	Land
Environmental Loading	CO_2 emissions from construction
	SO_2 Emissions from construction
	NO_X emissions from construction
	Annual CO_2 emissions from operation *
	Annual SO_2 emissions from operation *
	Annual NO_X emissions from operation *
Architectural Quality	Identity
	Scale / Proportion
	Integrity / Coherence
	Integration in urban context
Indoor Quality	Air quality
	Lighting quality
	Thermal quality
	Acoustic quality
Functionality	Functionality
	Flexibility
	Maintainability
	Public relations value

3. Generation of alternative solutions

A quick brainstorming session was carried out to generate possible strategies for solar/energy savings. The different strategies were grouped together into 5 main design schemes:

Reference case: Energy supply from district heating and distribution by radiators
Alternative 1: Energy supply from ground coupled heat pump and distribution by radiators
Alternative 2: Local electric radiators + well insulated windows
Alternative 3: Utilization of daylight in classrooms and group rooms. Increased floor to-ceiling height, elevation of windows, light reflecting surfaces.
Alternative 4: Natural/hybrid ventilation through the use of the shafts and stairways for exhaust air/solar chimneys.
Alternative 5: Photovoltaics (crystalline silicon) cladding on south part of ventilation towers (total 50 m²).

4. Performance prediction

The team did a performance prediction of the different solutions with respect to the different criteria. The predictions were based on experience, rules of thumb, and expert judgement. For the Life-Cycle Cost and the Resource Use criteria, the performances were expressed in terms of % change compared to the reference case.

The reference case received a score of 100% on all criteria. Thus, if one alternative performed 10% better than the reference case on a specific criterion, the alternative received a score of 90% (smaller is better). For the Architectural Quality, Indoor Quality, and Functionality, the proposed scale 0-10 (bigger is better, 5 is typical) was used.

The team briefly discussed these scales. They were not sure whether they were the most appropriate scales to use. Anyway, they decided to have a go with the proposed Task 23 scales.

The performance prediction was done using estimations based on rules of thumb and the experience and knowledge of the team members. The only tool was a calculator; no computer simulations were carried out. Some of the predictions were subject to long discussions, especially the ones related to economics, while others were settled quickly and with confidence.

Due to time limitations, alternative 5 (photovoltaics) was not included in this first round.

The results of the scorings were entered into to the Evaluation Worksheet. Star diagrams were produced, shown in Figure 10-4. Looking at the star diagrams, the design team realized that they might not have used the scales correctly. There were almost no distinctions between the scores for the different alternatives. The team decided to proceed with the weighting, and return to investigate the scaling problem in more detail after that.

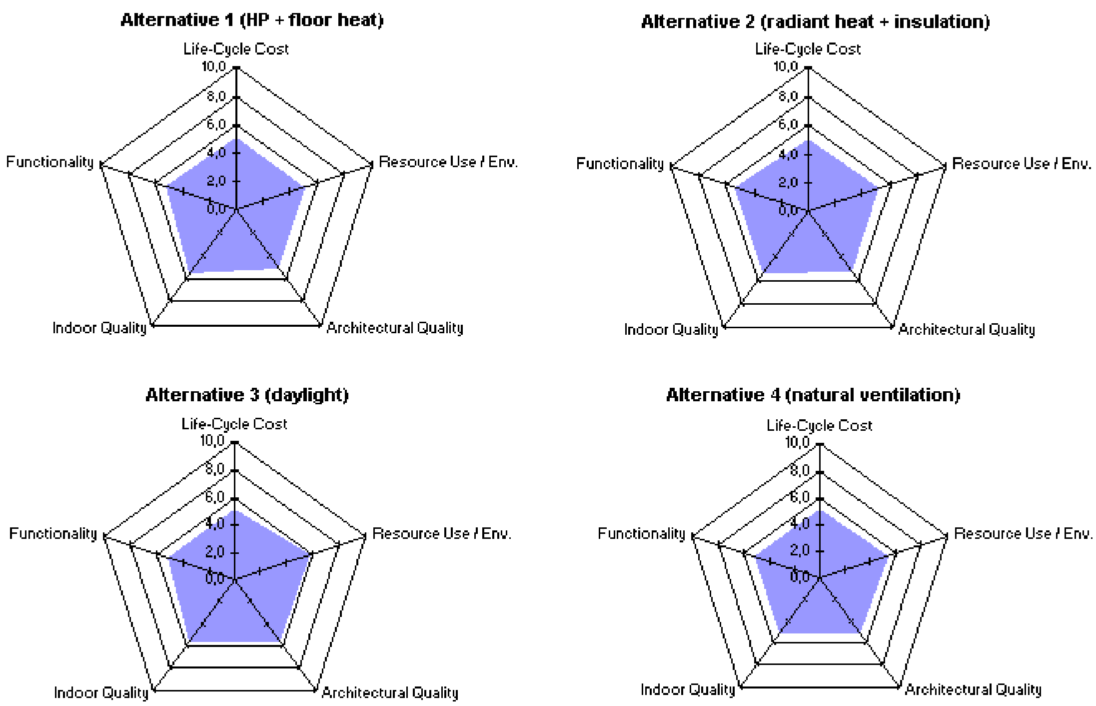


Figure 10-4. Star diagrams.

5. Weighting of criteria

The criteria and sub-criteria were weighted directly on a scale from 0 to 1 (bigger is better). The weights were produced through an open discussion among the team members where everybody except the process leader voiced his/her opinion and an agreement was reached. The main criteria were weighted first, then the sub-criteria. The result was as follows:

Table 10-2. Result of criteria weighting.

Criteria	Criteria weights	Sub-criteria	Sub-criteria weights
Life Cycle-Cost	0.8		
Resource Use & Environmental loading	0.8	Annual electricity	1.0
		Annual fuel	0.5
Architectural Quality	0.8	Identity	1
		Scale/Proportion	1
		Integrity/Coherence	1
		Integration in urban context	1
Indoor Quality	1	Air quality	0.8
		Lighting quality	0.8
		Thermal quality	1
		Acoustic quality	0.8
Functionality	1	Functionality	1
		Flexibility	0.9
		Maintainability	0.9
		Public relations value	0.5

6. Aggregation
Multiplying the scores on each criterion with the weights (performed by the evaluation worksheet), produced the following results:

Table 10-3. Total weighted scores on a scale from 0 to 10, where bigger is better and reference is 5.

Design scheme	***Total weighted score***
Reference case: Energy supply from district heating and distribution by radiators	*5.00*
Alternative 1: Energy supply from ground coupled heat pump and distribution by radiators	*5.12*
Alternative 2: Local electric radiators + well insulated windows	*5.11*
Alternative 3: Utilization of daylight in class rooms and group rooms.	*5.34*
Alternative 4: Natural/hybrid ventilation through the use of the shafts and stairways as for exhaust air/solar chimneys.	*5.09*

Thus, alternative 3 (daylight) seems to be the best scheme, while alternative 1, 2 and 4 get approximately equal values. However, the relative improvements in scores compared to the reference case are small. The best score is only 7% higher than the reference score.

7. Sensitivity analysis
This was not carried out due to time restrictions.

10.3 Lessons learned

The process of scoring the quantitative criteria was quite straight forward, because it was possible to calculate hard numbers for performances of the design schemes (i.e. energy consumption) and compare them to the reference case. However, the pre-determined scales did not turn out to be well suited for all the criteria. Only the middle of the scales were used, so the differences between the alternatives were small. To be able to better see the differences between the alternatives, the scales should have been smaller.

In scoring the quantitative criteria first, a basis for scoring the qualitative ones was established. In this way, the qualitative scales were implicitly linked to the quantitative ones. However, the relationships between the scales and the weights were not totally clear.

All the team members felt quite comfortable with using this kind of methodology, and the process went smoothly and without major difficulties. The participants especially felt it was a good way to structure the design work, thus making it more efficient. However, this positive reception may be due to the fact that all the participants had some experience with similar methods. Still, the team felt that they did not have enough information or accurate data so that they were able to predict all performances with certainty. In particular, they felt the need for more information about costs.

The team members found the exercise interesting, useful, and fun. Since they did not have the time to complete the exercise, they would like to try it again at another meeting. At this next meeting, the team would go on to investigate combinations of the alternative schemes.

However, the actual building project went so fast that there was no time for another meeting.

11 Case 3

11.1 Introduction

This case was a test of the MCDM approach that was conducted during the preliminary design phase for the construction of a new administration building for the Norwegian State Railways (NSB) in Oslo.

The organization of the design project is illustrated in Figure 11-1.

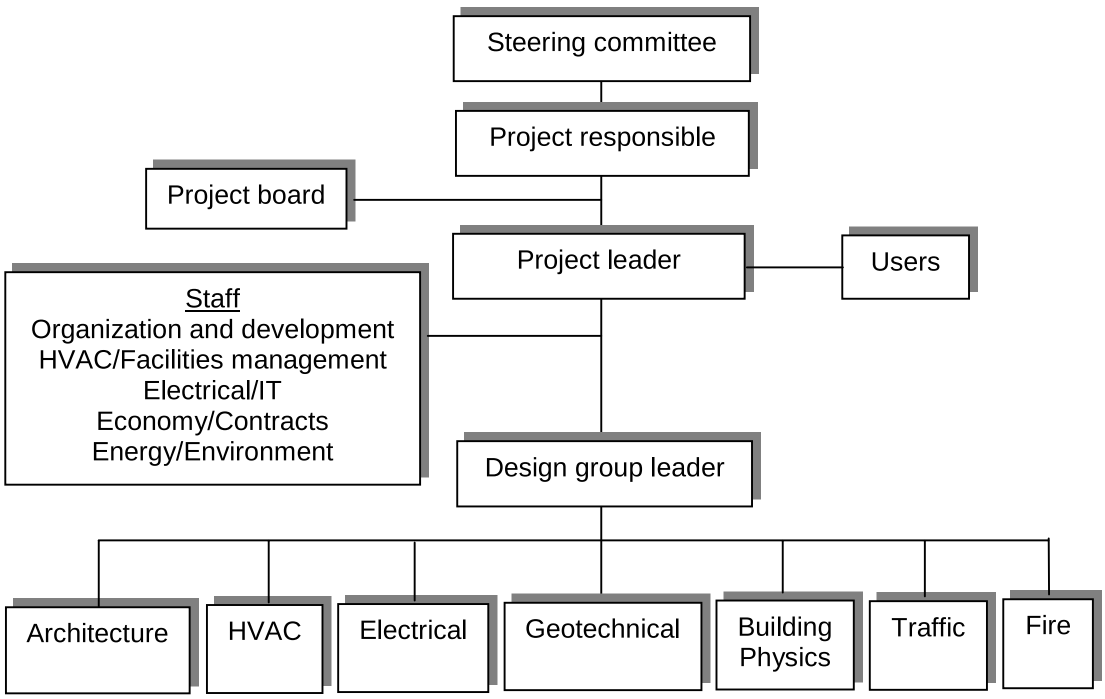


Figure 11-1. Design project organization.

The MCDM approach was introduced into the project in the late part of the preliminary design. Design criteria had been formulated, and a design concept had been proposed. Still, many factors concerning the energy system had not yet been evaluated or decided. The overall goals of the project were to develop a profitable building that should give a “positive impression to the public” and be a “benefit to the local environment”. Internally, the building should aim at “improving the well-being and production efficiency of the employees". The overall design criteria may be formulated as follows:

- safety
- environment
- functionality
- aesthetics
- cost effectiveness

The safety specifications were given as compliance to codes and standards. Environmental issues included energy use, pollution control, minimization of solid waste, and indoor environment, see Figure 11-2. With respect to functionality, the following key issues were stressed:

- flexibility (dynamics, future oriented)
- effective use of space (openness, communication, cooperation)
- maintainability

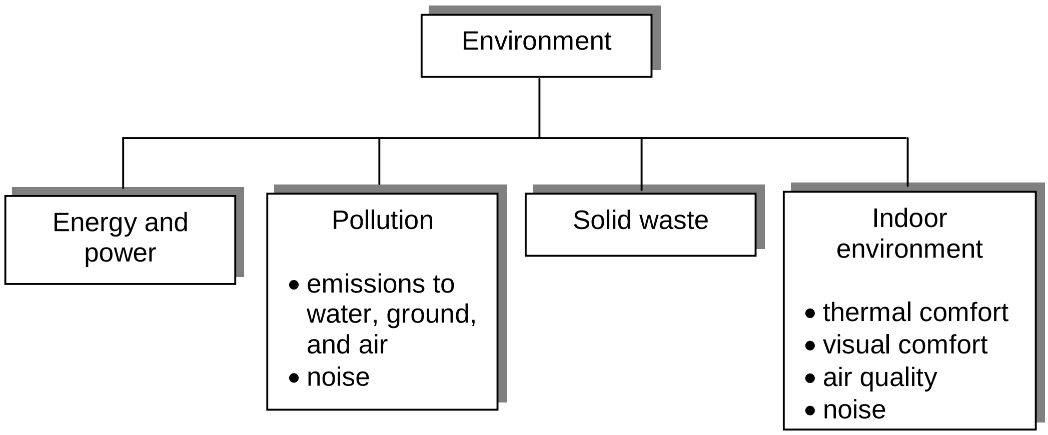


Figure 11-2. Structure of the criteria regarding environment.

The preliminary design at the time of the evaluation is shown in Figures 11-3 to 11-5. The building has a net floor area of approximately 25000 m^2 and includes 7 stories. It is set in a typical urban environment, surrounded by buildings of about the same height. The interior atrium has an exterior facade facing south.

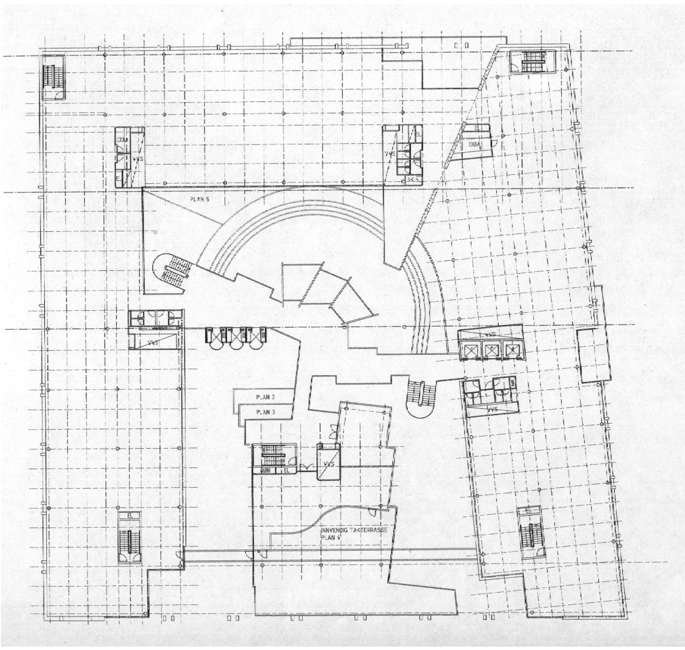


Figure 11-3. Floor plan (6th floor).

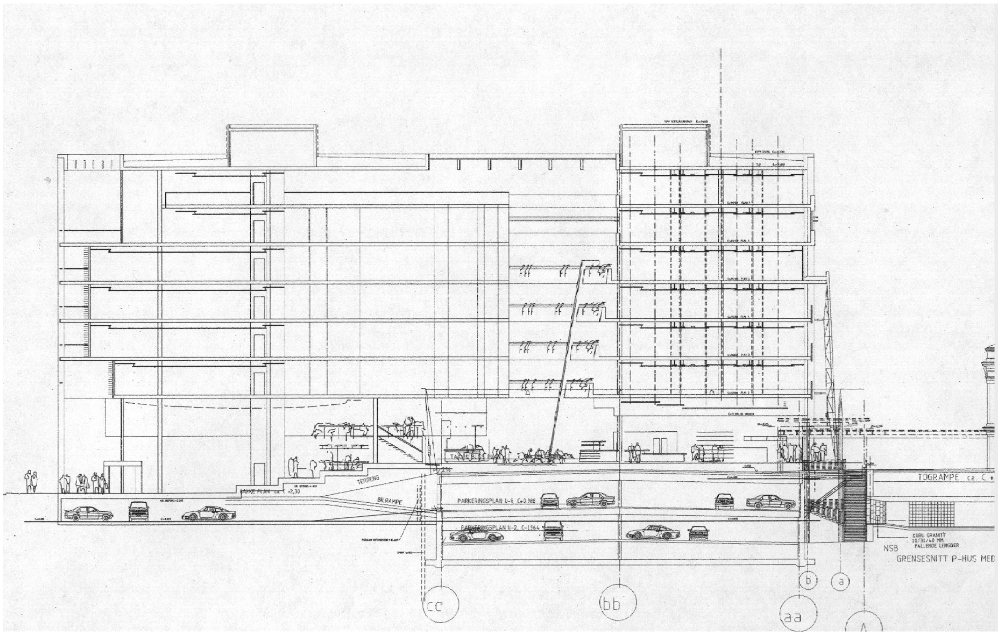


Figure 11-4. Section.

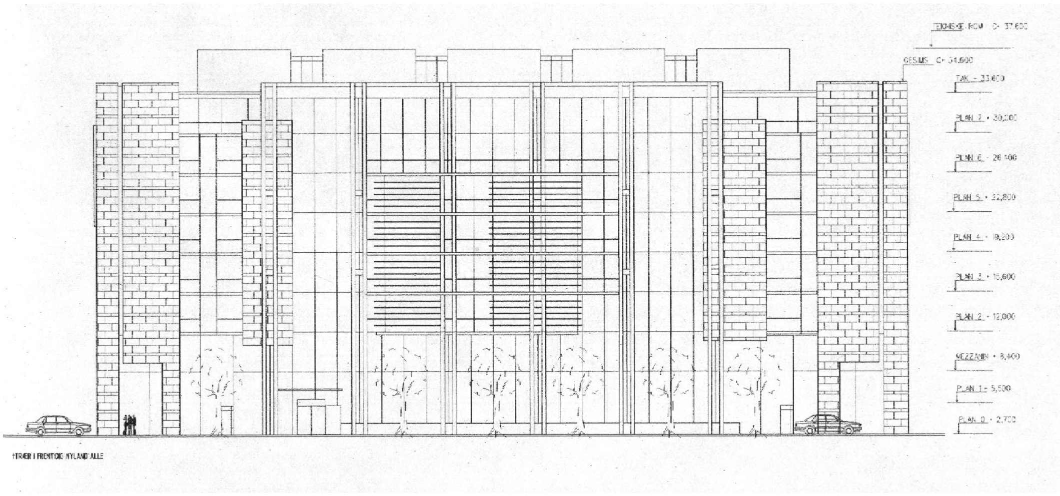


Figure 11-5. South facing facade.

11.2 The Process

The MCDM-approach was introduced to the design team and two members of the staff (responsible for HVAC/facilities management and energy/environment) at a meeting. The group found the approach interesting, and agreed to test it in their design work. They decided to do an evaluation of 4 alternative designs of the atrium, as follows:

Alternative 1: Double construction in the roof and facade of the atrium. Minimum air temperature in the atrium is 20°C.
Alternative 2: Single construction in the roof and facade of the atrium. Minimum air temperature in the atrium is 10°C.
Alternative 3: Single construction in the roof and double construction in the facade of the atrium. Minimum air temperature in the atrium is 10°C.
Alternative 4: Single construction in the roof and double construction in the facade of the atrium. Minimum air temperature in the atrium is 20°C.

The single construction is a double glazing with low-E coating. The double construction has an outer double glazing with low-E coating and a single inner glazing with low-E coating. The distance between the outer and inner glazing is approximately 1.0 m. This space is used for ventilation air which may filtered and heated as needed.

For the evaluation of the alternative atrium constructions, the following criteria were chosen to be most relevant:

- Environment:
  - energy consumption
  - thermal comfort
  - daylight availability
- Functionality
- Flexibility

- Aesthetics
- Cost effectiveness

Safety was not included because all alternatives were presumed to satisfy the safety requirements. Power consumption was not included in the environment because it was included in the cost effectiveness criterion. Also, pollution, solid waste and noise were not included in the environmental criterion because they were not considered to make significant differences for the alternative atrium constructions. Flexibility was defined to be "how easily the space could be changed to accommodate other, future uses". This might be a part of the functionality criterion, but it was kept separate because it was considered to be important enough to warrant this. The measurement scales were constructed as geometric preference scales based on Lootsma's theories. Table 11-1 shows an overview of the scales that were used for the different criteria. The relative scale was also used for the criteria weighting.

Table 11-1. Measurement scales (a progression factor of 2 was used for the energy and cost scales).

Absolute scale	**Relative scale**	**Energy-consumption* ($kWh/m^2/year$)**	**Life Cycle Costs** (NOK/year)**	**Thermal comfort Aesthetics Functionality Flexibility Daylight**
10 – Excellent	10 – Preferred	110	K_{min}	10 – Excellent / Preferred
9	9	112	K_{min} + 15.000	9
8 – Good	8 – Somewhat less preferred	115	K_{min} + 50.000	8 – Good / Somewhat less preferred
7	7	120	K_{min} + 100.000	7
6 – Fair	6 – Less preferred	130	K_{min} + 250.000	6 – Fair / Less preferred
5	5	160	K_{min} + 500.000	5
4 – Min. acceptable	4 – Much less preferred	200	K_{min} + 1.000.000	4 – Min. acceptable / Much less preferred

**This scale is based on a goal for energy consumption of 75% of the norm for cost effective low energy buildings (which results in a goal of 110 $kWh/m^2/year$). The maximum acceptable energy consumption was set to 75% of the average energy consumption for existing office buildings.*

***The cost scale is based on the cheapest alternative being the most preferred. This alternative has a life cycle cost of K_{min}. The lowest score (minimum acceptable) was defined to a cost of K_{min} + 1.000.000 NOK/year.*

The energy consumption of the building was calculated by the HVAC engineer using computer simulations and rules of thumb. The results are given in Table 11-2.

Table 11-2. Specifications of Energy scores.

Absolute scale	Relative scale	Energy consumption (kWh/m²/year)	Ranking of alternatives
10 – Excellent	10 – Preferred	110	
9	9	112	
8 - Good	8 – Somewhat less preferred	115	Alternative 3 (115)
7	7	120	Alternative 2 (120)
6 – Fair	6 – Less preferred	130	
5	5	160	Alternative 1 (150) Alternative 4 (170)
4 – Min. acceptable	4 – Much less preferred	200	

The cost estimations were carried out by the HVAC engineer, assisted by a sub-contractor specializing in cost assessment. Details of the cost estimations are given in Figure 11-6. The resulting life cycle costs are illustrated in Figure 11-7.

Alternative 1: Double facade and double roof construction, T_{min} = 20°C

Extra glass in facade:	+ 1800 m² · 3200 NOK/m² = 5.760.000 NOK
Extra glass in roof:	+ 900 m² · 2600 NOK/m² = 2.340.000 NOK
No in-glazing*:	- 4.200.000 NOK
No extra ventilation:	- 300.000 NOK
Less cleaning:	- 75.000 NOK/year
Higher energy consumption:	+ 150.000 NOK/year

Alternative 3: Double facade and single roof construction, T_{min} = 10°C

Extra glass in facade:	+ 1800 m² · 3200 NOK/m² = 5.760.000 NOK
Less cleaning:	- 60.000 NOK/year
Less energy consumption:	- 25.000 NOK/year

Alternative 4: Double facade and single roof construction, T_{min} = 20°C:

Extra glass in facade:	+ 1800 m² · 3200 NOK/m² = 5.760.000 NOK
No in-glazing*:	- 4.200.000 NOK
No extra ventilation:	- 300.000 NOK
Extra radiative heating:	+ 450.000 NOK
Extra floor heating:	+ 75.000 NOK
Less cleaning:	- 60.000 NOK/year
Higher energy consumption:	+ 200.000 NOK/year

*Figure 11-6. Cost data (relative to alternative 2: Single facade and single roof construction, T_{min} = 10°C) used in the estimation of life cycle costs. *In-glazing means that some of the interior zones within the atrium are glazed in when the atrium temperature, T_{min} = 10°C (i.e. reception, some offices and meeting rooms, café, and library).*

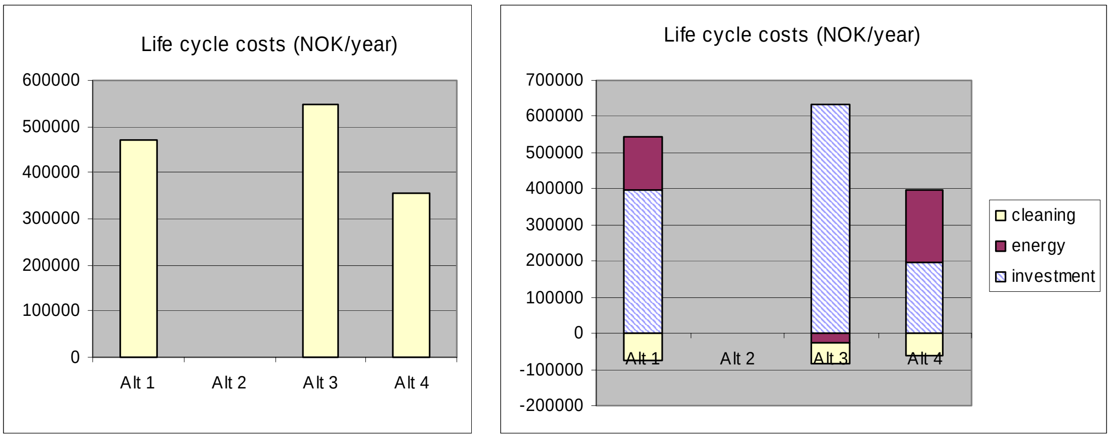


Figure 11-7. Life cycle costs (relative to alternative 2). The graph to the right shows the relative contributions from investment costs (hatch), cleaning costs (light shade), and energy costs (dark shade).

Thermal comfort and daylighting were evaluated using dynamic computer simulations and qualitative expert judgements of the HVAC engineer, and documented using verbal terms. The arguments for the thermal comfort and daylighting scores are summarized in Table 11-3 and Table 11-4. In the column labeled "specification", the arguments given for the scores are summarized.

Table 11-3. Specification of Thermal Comfort scores.

Alternative atrium constructions	**Score**	**Specification**
Alternative 1: Double construction in roof and facade. T_{min} = 20ºC	Excellent (10)	Little cold radiation and cold draft during wintertime. Possibilities for ventilation without drawing polluted air into the atrium and without creating a feeling of "wind".
Alternative 2: Single construction in roof and facade. T_{min} = 10ºC	Good (8)	Danger of getting expectations of fully conditioned space anyway, and then this construction would cause discomfort.
Alternative 3: Single construction in roof and double in facade. T_{min} = 10ºC	Excellent (10)	Good control of thermal comfort summer and winter.
Alternative 4: Single construction in roof and double in facade. T_{min} = 20ºC	Good (8)	Good climatic control at the bottom part of the atrium, summer and winter. Ventilation of upper parts will cause draft and soiling.

Table 11-4. Specification of Daylighting scores.

Alternative atrium constructions	**Score**	**Specification**
Alternative 1: Double construction in roof and facade. T_{min} = 20ºC	Fair (6)	Give the lowest daylight level. This is important for the offices facing the atrium.
Alternative 2: Single construction in roof and facade. T_{min} = 10ºC	Excellent (10)	Gives the highest daylight level.
Alternative 3: Single construction in roof and double in facade. T_{min} = 10ºC	Good (8)	Alternatives 3 and 4 are similar with respect to daylight level, and are in between alternative 1 and 2.
Alternative 4: Single construction in roof and double in facade. T_{min} = 20ºC	Good (8)	Alternatives 3 and 4 are similar with respect to daylight level, and are in between alternative 1 and 2.

The functionality and flexibility criteria were evaluated by the architect and the design group leader. Therefore, there are two sets of evaluations shown in Table 11-5 and

Table 11-6. Aesthetics was evaluated by the architect only, shown in Table 11-7.

Table 11-5. Specification of Functionality scores.

Alternative atrium constructions	**Score**	**Specification**
Alternative 1: Double construction in roof and facade. T_{min} = 20ºC	Excellent (10) Excellent – (9)	There is no need for extra efforts for heating/cooling the cafeteria. Takes up space.
Alternative 2: Single construction in roof and facade. T_{min} = 10ºC	Fair (6) Fair (6)	Local efforts needed to make the cafeteria acceptable. The meeting rooms next to the atrium cannot be used in parts of the year. Large cleaning needs. More limitations with respect to places to sit.
Alternative 3: Single construction in roof and double in facade. T_{min} = 10ºC	Fair/Good (7) Good (8)	Some efforts needed to make the cafeteria environment acceptable. Similarly for meeting rooms at walking bridges. Large cleaning needs. Less cold surfaces than for alternative 2, thus less limitations with respect to places to sit.
Alternative 4: Single construction in roof and double in facade. T_{min} = 20ºC	Fair – (5) Excellent/ Good (9)	Too high energy consumption.

Table 11-6. Specification of Flexibility scores.

Alternative atrium constructions	**Score**	**Specification**
Alternative 1: Double construction in roof and facade. T_{min} = 20ºC	Excellent (10) Excellent (10)	May be used for public meetings, concerts, etc. and shopping mall.
Alternative 2: Single construction in roof and facade. T_{min} = 10ºC	Fair – (5) Fair + (7)	Limitations on usage parts of the year. More limitations on places to sit.
Alternative 3: Single construction in roof and double in facade. T_{min} = 10ºC	Fair/Good (7) Good (8)	Some limitations on usage parts of the year. Less cold surfaces than for alternative 2, therefore less limitations on places to sit.
Alternative 4: Single construction in roof and double in facade. T_{min} = 20ºC	Excellent (10) Excellent – (9)	

Table 11-7. Specification of Aesthetics scores.

Alternative atrium constructions	**Score**	**Specification**
Alternative 1: Double construction in roof and facade. T_{min} = 20ºC	Fair (6)	Bulky construction. More mullions, fastening devices, etc.
Alternative 2: Single construction in roof and facade. T_{min} = 10ºC	Excellent – (9)	Slim construction – as simple as possible.
Alternative 3: Single construction in roof and double in facade. T_{min} = 10ºC	Good – (7)	
Alternative 4: Single construction in roof and double in facade. T_{min} = 20ºC	Good – (7)	

Some of the “specifications” show that other criteria than the one being evaluated have sometimes been mixed into the evaluations. In the arguments for the scoring for the thermal comfort criterion, maintenance issues (soiling) and air quality issues (drawing in polluted air) were given. Some of the background descriptions for the functionality scores might relate to costs (extra efforts needed, takes up space), and maintenance (large cleaning needs). Also, we see that some of the functionality issues included are very much related to comfort issues (cold surfaces and places to sit). It might be OK to draw in other issues like this if it is done in a consistent manner, and if the other issues are not part of other criteria that are included in the evaluation. However, double counting must be avoided. Inconsistencies or diffuse statements should lead to discussions about the definition of the criteria and about what criteria to include. One of the scorings for alternative 4 on the functionality criterion is clearly based on arguments related to energy use, which should be accounted for in the energy criterion only. After reconsideration, this score was changed to 9.

The project management group discussed the results of the performance scorings in a new meeting. They studied the arguments and data used to score the individual alternatives, and they looked at the star diagrams shown in Figure 11-8, the preliminary weights shown in Figure 11-9, and the final weighted scores shown in Figure 11-10. Two of the team members had given preliminary weights to the criteria (see Table 11-8), and the mean values of these weights were used in the presentation of the total weighted scores (in Figure 11-10).

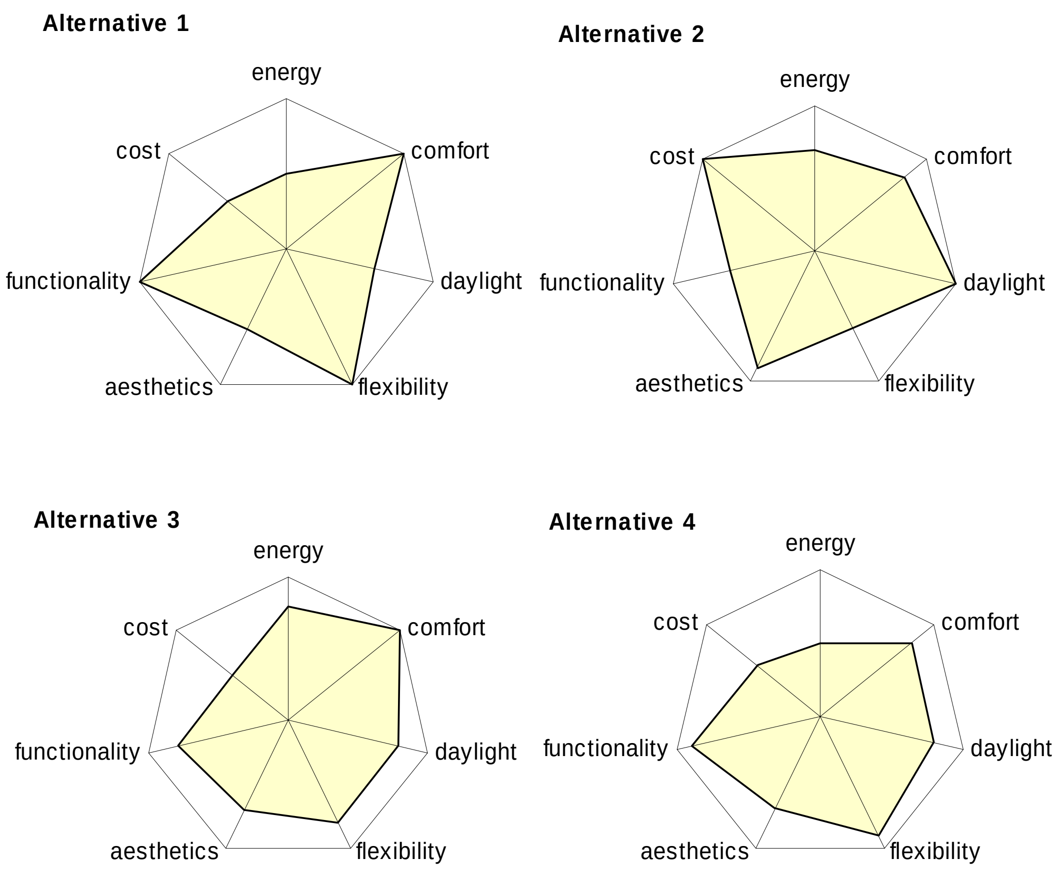


Figure 11-8. Star diagrams for the 4 alternative atrium constructions.

Table 11-8. Preliminary criteria weighting given by two of the staff members.

Relative scale	Preliminary weighting, staff #1	Preliminary weighting, staff #2
10 – Preferred	Cost effectiveness	Thermal comfort, Flexibility, Functionality
9	Aesthetics, Functionality	Energy, Costs
8 – Somewhat less preferred	Energy	
7	Comfort, Daylight, Flexibility	Aesthetics, Daylight
6 – Less preferred		
5		
4 – Much less preferred		

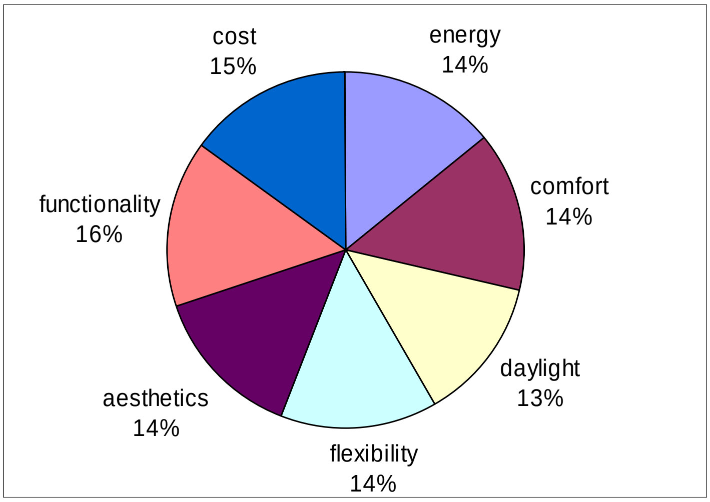


Figure 11-9. Chart showing the relative importance weights of criteria that was used in creating the final scores in Figure 11-10.

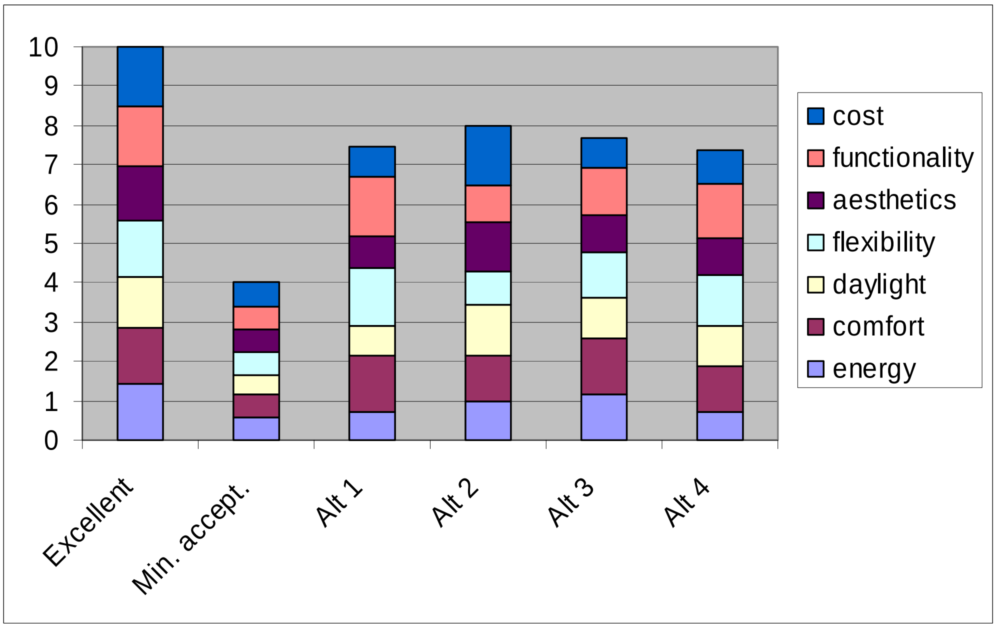


Figure 11-10. Total weighted scores for the alternative atrium constructions with the contributions of the different criteria indicated. (Imaginary alternatives with overall excellent performance (10) and minimum acceptable performance (4) are included as references).

The group discussed the performance assessments and the importance of the criteria. Several arguments were raised to document why different criteria were considered to be important. The performance scale for costs was questioned. The participants felt that the preference scale for cost-assessment should be curved, but found it a bit difficult to specify the end points. They suggested that it might be better to keep the costs separate from the other criteria, i.e. to do a "cost – quality" assessment where the cost of each alternative solution is posed against the other (aggregated) qualities. The team questioned some of the cost data, and decided that this needed further investigation. Also, energy and thermal comfort issues were further discussed, e.g. the minimum acceptable temperature level and the corresponding functionality and energy consumption of the atrium. They decided that the thermal comfort issue needed further investigation, e.g. to see how long periods of time the temperature level would float below, say 18°C, in alternatives 2 and 3.

The group concluded that they had one alternative with high costs and high energy use that performed well with respect to functionality and comfort (alternative 1) and another alternative with low costs that did not function very well with respect to comfort and functionality (alternative 2). Also, alternative 4 was not considered good enough with respect to energy, and alternative 3 was questioned with respect to functionality and comfort. The team asked the question "can we not do better than this?", and started discussing other alternatives. They discussed temperature control strategies, and considered different roof and facade constructions, and local heating installations.

11.3 Lessons learned

Due to external circumstances, this third case study received much less time than was originally planned. It was the intention in this case to introduce the MCDM approach from the beginning of the planning process, and follow the entire process to the end. However, as it turned out, the MCDM approach was introduced in the middle of the planning process, and was only used for evaluating a part of the design (i.e. the glazing of the atrium). There was little time to interactively define and discuss the criteria and the results, and there was no time for iterations in order to follow the evaluation to the final choice of design strategy.

Nevertheless, the case study provided information that can be used to draw some conclusions. First of all, the participants seemed to understand the scaling and weighting concepts well, and they were able to quickly give evaluations of the different alternatives on the pre-defined scales. However, the participants found it somewhat difficult to set end points on the cost scale. It was therefore suggested that it might be better to keep the costs separate from the other criteria. Also, some mix-ups of different criteria were encountered (e.g. including energy issues in the functionality criterion). However, this problem could easily have been avoided if there had been time for a proper discussion and definition of the criteria and the alternatives. It was interesting to see that the assessments of functionality and flexibility by two different members of the design team, were quite similar. This suggests that their comprehension of the scales were similar (given, of course, that their actual performance assessments agreed).

In summary, the case study suggested that the MCDM approach might be a useful way of assessing and presenting the overall performance of potential design solutions. However, some problems were encountered with respect to constructing a suitable performance scale for cost-assessment. Apart from this, the presentation of the results seemed to be useful in order to get a picture of the overall performance of the alternative design solutions. It also provided a common reference for a structured discussion of design criteria and for the performance assessment of alternatives, and it spurred the search for better solutions. However, the test was too limited to draw any final conclusions about whether such an approach would improve the overall design process.

12 Conclusions

The background of this thesis was that solar building design needs to address many different criteria that are complicated and often conflicting. In order to deal with the range of different technologies and design criteria, different design experts need to be involved. Therefore, it may be difficult to evaluate the overall "goodness" of a proposed design solution. Also, the communication between design professionals and the client may be complicated.

The hypothesis of the thesis was that a structured approach to evaluation of design solutions would help promote a solar design process where all the important criteria would be included in an appropriate and efficient manner.

An investigation of the building design process confirmed that evaluation of alternative design solutions is an important task, but it is closely connected to other tasks such as problem formulation, generation of alternatives, and performance prediction. The investigation also showed that design decisions are often based on experience, "gut feeling" and intuition. The quantitative measures are often better documented than the qualitative ones, and therefore, they tend to receive more attention. All this suggested that a formal evaluation approach might be useful.

A few multi-criteria evaluation models have been proposed and used in building design. The models resemble somewhat the Multi-Criteria-Decision-Making (MCDM) methods found within the fields of operational research, management science, and physical planning. However, very little formal documentation was found about their theoretical basis or their rationale for use. Also, there was little evidence found of how they fit into the design process. This spurred a comprehensive search within the area MCDM methods. The thesis explores a range of different MCDM models to test how well they fit into a building design framework.

It was found that many of the existing MCDM models are very complicated and difficult to understand and use. Therefore, it was recommended to start with the most simple of the models for a first introduction into building design. However, it was found that a crucial problem of these models is how to take care of the link between the measurement scales and the importance weights. The weights are essentially re-scaling parameters that convert all scales into a common unit so that they can be aggregated. This issue has not received much attention in the few models that were found in building applications.

Therefore, a thorough discussion of measurement and preference theory was included in the thesis. Some techniques for establishing the link between the scales and the weights were proposed. One of the techniques involved using trade-off or indifference checks. However, this technique was found to be quite cumbersome and time-consuming. The experience from the case studies indicated that the design team tended to disregard these checks. Therefore, another approach for taking care of the scaling/weighting link was proposed. This technique involves using logarithmic preference scales both for measuring the performance of alternatives and for criteria weighting. It is based on a theory by Freerk A. Lootsma, which suggests that humans are sensitive, not to marginal, but to relative changes in value, and that this might be mapped onto scales containing a certain number of preference categories. Lootsma shows how human beings follow a uniform pattern in many unrelated areas when they subdivide a particular scale into subjectively equal subintervals. The dB-scale for measuring sound intensities, is an example of this. Although the arguments for using these scales are convincing, it is not certain that all decision-makers of building design are able to map their preferences onto such scales. In case 3, these scales were tested. Geometric scales with a progression factor of 2 were used for mapping the preferences of the quantitative criteria. The results suggested that the scales worked well for categorizing alternatives on all criteria except for costs, were some problems were encountered in setting the end points of the scale. One solution to this problem could be to leave the costs out of the aggregation, and do a "cost-quality" analysis. Another solution could be to test out different variants of the logarithmic coding in a range of building projects, using different end points and different progression factors. This may result in a set of "standardized" performance scales that could be used to help the decision-makers model their preferences.

To conclude, the method based on Lootsma's theories seems to help simplifying the evaluation process, while ensuring the link between the scales and the weights. However, more research should be carried out to characterize the preferences used by decision-makers in building projects.

Also, it was found that there is a need for further investigation of how to fit MCDM-approaches into the building design practice. Therefore, the thesis includes a discussion of how the formal evaluation model may be integrated into the design process. This was based on general building design theory and ideas from more structured design approaches such as systems analysis and systems engineering. It was found that the different tasks of building design were very much intertwined. To be able to do an evaluation, it is necessary to have some performance criteria and some alternatives to compare. Also, some predictions of the alternatives' fulfillment of the criteria, are required. The specification of performance criteria may lead to generation of alternatives, and the evaluation of alternatives may lead to a revision of the criteria. Thus, the evaluation task was placed into an iterative process of problem formulation, generation of alternatives, and performance prediction. A proper specification of the values of the stakeholders was found to be an important prerequisite for generating and evaluating alternatives. This is because it is these values that determine how good the design really is (in the stakeholders' view). By encouraging the decision-makers to explicitly formulate design criteria, discussions about values are initiated. It also helps specifying the meaning of terms which promotes a common understanding of what is important to focus on. This is especially important when there are qualitative criteria. For example, what does the criterion "good indoor quality" mean? It may have different meanings for different people. Using a structured approach for eliciting and specifying criteria also ensures that all relevant issues are included, and focuses the attention on the most important issues. In this way, the set of criteria will guide the search for information so that no time is wasted on collecting information that turns out to be of no relevance. The experience from the test cases showed that the elicitation and hierarchical structuring of criteria helped the design teams to focus on the important issues, while at the same time keeping the overview.

From the investigation of the building design process in general and solar design in particular, the following requirements of the multi-criteria evaluation approach were found:

- It should be a relatively open framework.
- It should be usable for the early design phase.
- It should be simple and quick to understand and use.
- It should promote understanding of the holistic design problem.
- It should handle judgements and values.
- It should be an aid to focus on the most important issues.
- It should handle uncertainty.

Based on these requirements, a multi-criteria decision-making framework for solar design was developed. The approach was tested in 3 design projects. This empirical evidence is of course quite limited, and further testing of the approach in practical design projects is needed in order to conclude whether or not the requirements have been met. However, based on the test cases and the theoretical discussion in this thesis, the following conclusions may be drawn with respect to fulfillment of the different requirements:

It should be a relatively open framework.
The suggested approach is really quite flexible. The case studies showed that the method could easily incorporate different types of criteria, different numbers of criteria, and it worked for different kinds of building projects involving different kinds of people. Also, it was shown that the method might be used at different levels of detail in different stages of the design process. The team members may choose between a variety of techniques and tools for problem structuring. Flexibility is also supported by the stepwise procedure for evaluation, starting with a simple side-by-side comparison of alternatives and ending up with a numerical additive weighting method. Also, the design team members may choose between different techniques for scoring and weighting.

It should be usable for early design phase.
In Case 2, the approach was tested in the schematic design phase. The process went smoothly and the team members all felt comfortable with the method. Some problems were encountered, but these were due to the fact that the method was not fully developed, and was accounted for in the further development of the method. In the early design phase, decisions often need to be based on expert judgements. The method seems to be well suited for decisions based on judgmental evaluations. However, more testing is needed in order to confirm that the approach is useful in improving the decisions in the early design phase.

It should be simple and quick to understand and use.
The formal scoring and weighting procedures may at first appear foreign to building designers. On the other hand, the experience from the case studies suggested that given some explanation of the purpose and basic assumptions, the method is not difficult to understand or use. The main problem is the link between the performance scales and the importance weights. The evidence of whether or not people are able to appropriately adjust the weights in accordance to the scales, is mixed. The use of consistency checks by means of trade-off/indifference questions may be cumbersome and time consuming. In the case studies, where there was a shortage of time, consistency checks were only done superficially. The approach based on Lootsma's logarithmic categorization, may be a way around this. However, the decision-makers may have trouble accepting these kinds of scales. Also, they may still find it difficult to specify the end points of the scales. In case 3, the participants had some difficulties using this scale for the cost criterion. The problem could be solved by presenting some pre-defined scales constructed from surveys of building projects.

It should promote understanding of the holistic design problem. It should handle judgements and values alongside "hard" data.
The results of the case studies suggested that the structure of criteria and the standardized measurement scales provided a common reference to help organize the work and reach a common understanding and consensus concerning design strategies. The approach offers a formal way to handle the judgements and qualitative values alongside the quantitative data. By making the judgements and values explicit, the method ensures better documentation of the choices and produces an audit trail. This is particularly important for issues of general public value, for example environmental issues. The method does not attempt to quantify the qualities; rather it takes the qualitative judgements as a basis and transforms all the assessments into a qualitative scale. This encourages the decision-makers to really consider the value of the hard data, as formulated by Saaty (1994):

"Hard data about the world must be transformed to a kind of data that can be integrated with other qualitative information needed to think through a plan consistently. Hard data cannot be used for this purpose in the raw form it is obtained from natural measurement. It must take the same form as the rest of our soft data to allow us to combine and manipulate it to make it serve our goals and values. These goals and values must be understood with the same kind of soft data. That is how the world is assimilated by the mind with satisfaction."

Explicit weighting tends to force open the "black boxes" between the design professionals themselves, and between the design professionals and the client and the users of the building (and other stakeholders). This should promote knowledge transfer and support a common understanding of the overall goodness of a design solution. It also makes the decisions taken during the design process more traceable, thus it may serve both to document and to better understand the design work.

It should be an aid to focus on the most important issues.
Through the techniques for problem structuring, and through the weighting system, the method seeks to focus attention on the issues that are most important to the decision-makers. The case studies suggested that both the hierarchical structuring of

criteria and the weighting procedure were useful tools to streamline the work and to avoid getting bogged down with insignificant issues.

It should handle uncertainty and fuzzyness.
The framework is able to handle uncertainty through the use of sensitivity analysis, or alternatively to add conventional probability assessments to the quantitative evaluations. Case 1 demonstrated that incorporating a sensitivity analysis in the framework worked well. Used with skill, the sensitivity analysis may give a good overview of the uncertainties of the assessments. The qualitative measurement scales seemed to be well suited for handling fuzzy or vague value statements.

In general, more testing is needed in order to find whether the proposed approach really will improve solar design processes. Due to limited time, the tests have only included parts of the design process. Ideally, one needs to test the approach by following the entire design process, and maybe even include the construction and use phases in order to check if the approach really leads to improvements. Also different types of building projects need to be tested, involving different kinds of people and organizations.

The approach needs to be further refined and streamlined if it is going to fit smoothly into the design process. The success of the MCDM-methodology is dependent on the participants' understanding of the underlying theory. In the case studies, the process was lead by a person that was knowledgeable about MCDM theory (me). In real building projects, the leader of the MCDM-approach will typically be the design team leader. It is questionable whether it is realistic to expect that project leaders are able or willing to adopt such an approach, since it requires some time and interest in learning about the theory. An interactive computer program may help ease the learning and use of the approach. However, the computer program needs to be carefully designed to promote discussion and reflection and to avoid appearing as the producer of "the one right answer to the problem".

In principle, the approach should not only be useful for solar design, but also for general building design, especially where many complex design issues are present (e.g. environmental loading). However, it is particularly useful for solar design because it is typically more complex than conventional design tasks. In solar design there are many different technologies and strategies to be considered, and they are often very much interacting and dependent on each other and external factors like climate, use patterns, etc. In addition, solar technologies are developing very fast, and they need to be considered in a life-cycle perspective. Also, sustainability is a central issue of solar design, and this is an issue that is very complex and should be documented to the larger society. Therefore, solar design calls for the involvement of many different professionals, and cooperation, communication, and documentation are imperative for its success.

To sum up, the proposed framework seems promising with respect to improving the quality of decisions in the early phases of solar design because it encourages more carefully balanced and integrated evaluations. All the case studies suggested that the structuring of values and objectives into separate criteria seemed to be natural and logical to the participants. This also helped structure the discussions in the team, and provided a common reference for the design work. Also, the approach makes values and judgements explicit and promotes better documentation of the choices. Hopefully, this will make people more knowledgeable about all the different issues of solar design. Whether or not this will be a useful step towards making better solar buildings, remains to be seen.

Definitions

a-Si
Amorphous Silicon (used to denote type of photovoltaic cell).

Attribute
The most common usage of this term seems to be a characteristic of the options being evaluated which is measurable against some objective of subjective yardstick, i.e. a performance measure. Thus, each alternative can be characterized by a number of attributes, for example the energy consumption, the cost, or the aesthetics of a building. It is often used interchangeable with objective.

c-Si
Crystalline Silicon (used to denote type of photovoltaic cell).

Criterion
The dictionary definition of the term is standards of judgement or rules to test acceptability. In the MCDM literature it is used interchangeably with *objective* and *attribute*. The meaning of criterion is close to the meaning of objective, i.e. a reflection of the desire of the decision-maker that indicates the direction of change desired. Examples of criteria of building design are “minimum energy consumption”, “minimum cost”, “good aesthetic qualities”, etc.

Constraint
A constraint is a limit on the values that attributes and decision variables may assume. For examples, there may be an upper limit to the energy consumption of a building, specified in the building code.

Decision-maker
The phrase decision-maker is used throughout this thesis in general terms to mean an individual, an organization or any other decision-making entity.

Expected Utility
Daniel Bernoulli (1738) first suggested replacing the criterion of expected value with the criterion of expected utility. The expected utility theory suggests that each level of an outcome is associated with some degree of pleasure or net benefit, called utility. The expected utility of a certain choice is the weighted sum of the utilities of its outcomes, each multiplied by its probability (Bazerman 1998).

Expected Value
The expected value of an alternative is the weighted sum of all potential outcomes associated with that alternative multiplied with the probabilities of the respective outcomes (Bazerman 1998).

Goal
A goal defines some desirable level of achievement with respect to an objective. Goals are a priori values or levels of aspiration that are to be either achieved or not exceeded. Thus while objectives give the desired direction, goals give a desired (or target) level to achieve.

Multiple Attribute Decision Making (MADM)
Evaluation problems that are concerned with the evaluation of, and possible choice between, discretely defined alternatives. A survey of MADM methods is given in Appendix A.

Multiple Objective Decision Making (MODM)
*D*esign problems that are concerned with the identification of a preferred alternative from a potentially infinite set of alternatives implicitly defined by a set of constraints.

Multi Attribute Utility Theory (MAUT)
The process of estimating the scores and measuring impacts is fraught with difficulties. One way of handling this problem is to assign some probability values to the scores and impacts. The problem can then be recast as one that seeks to evaluate the expected utilities of the alternatives, seeking to identify the alternative with the highest expected utility value and define this as the best one. This is usually referred to as the MAUT problem. It has been extensively described by two of its proponents, Keeney and Raiffa (1976), as an appropriate way of aiding in a decision process.

O&M
Operation and maintenance.

Objective
An objective defines the direction of preference. Objectives are reflections of the desires of the decision-maker and they indicate the direction of change desired. An objective is something to be pursued to a maximum extent.

Preference Function
Defines the nature of the decision-maker's preference for a particular attribute

Probability
The concept of probability conveys the likelihood that any particular outcome will occur. A probability of 1.0 represents certainty that an event will occur. A probability of 0.0 represents certainty that an event will not occur (Bazerman 1998).

PV
Photovoltaics. A PV system is a system that converts solar energy into electricity using the photovoltaic principle (solar cells).

Risk
In everyday usage, risk means that the consequences of a decision are uncertain.

Stakeholder
A stakeholder is a person or group of people that has interests in a project or is affected by a project.

Value Function, Utility function
Defines the nature of the decision-maker's preference for a particular attribute.

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