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INTEGRATED LIFE CYCLE DESIGN
Application to Concrete Multi-Dwelling Buildings

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ABSTRACT

Design and procurement based on whole life appraisal may enhance functional quality and, thus, the overall quality and cost-effectiveness of buildings. Empirical studies support this claim. However, only a small proportion of building projects actually adopt life cycle design principles. With regard to this, whole life appraisal is examined by considering design procedures and the nature of the product; in this case Swedish concrete multi-dwelling buildings. The primary approach adopts life cycle costing, life cycle assessment and service life planning in the concept of integrated life cycle design. A field study of concrete multi-dwelling buildings has explored the practicability of this approach in terms of the application of life cycle thinking during design, life cycle cost estimating and accuracy in predicting energy use. Parameter studies have been conducted to assess potential consequences in the life cycle perspective. General methods for multiple criteria decision-making and their application on buildings are reviewed and furthermore, one simplified life cycle design method is outlined. The conclusions are, i: that life cycle design methods and data available are adequate enough to determine choices during the design phase, and ii: that there is a large potential with regard to improved life cycle economy and environmental performance to be exploited.

PREFACE

In Sweden, as in many other countries, concrete is the most frequently used construction material for multi-dwelling buildings. However, in the design of such buildings, many potentially favourable properties of concrete are often not optimally utilised. There are many, sometimes conflicting, requirements on a building, put forward by different partners involved in building; owner, contractor, resident, society. Such requirements concern economy, energy use, consumption of recourses, comfort, etc. Particularly, the life cycle perspective in terms of economy, ecology and performance must be considered at the design of buildings. This project was started in order to investigate the possibility of concrete of satisfying all these requirements and in order to develop tools that might be used for design of buildings considering all requirements in a rational manner.

My supervisor has been Professor Göran Fagerlund, whom I would like to thank for his inspiration and commitment. I would also like to express my gratitude to the following group of people for their valuable input: Bo-Erik Eriksson, Christer Ljungkrantz, Professor Asko Sarja, Birger Söpler and Professor Sven Thelandersson and Fredrik Winberg.

The author gratefully acknowledges the financial support of the Swedish Foundation for Strategic Research /SSF/ and Cementa AB, as co-sponsor, for the project, ‘The Optimal Concrete Building’, which forms part of the Swedish national graduate school and research program, *Competitive Building*.

SUMMARY

The characteristics and the context of buildings

The construction sector is sometimes referred to as the 40% sector, indicating its great impact on society. Resource use, waste, economy and also social dimensions, commonly designated sustainability criteria, are thus to a considerable extent dependent on the efficiency of construction and the quality of the built environment. It is, therefore, crucial that the sector contributes to sustainable development.

Buildings normally stand for a long time, which emphasizes the importance of the life cycle perspective. Life cycle appraisal is, however, rarely used in the design process today. A building has several characteristics or attributes to match the many different requirements it is subject to. Some of the attributes are variables that can be expressed in performance classes, for instance sound insulation, while others such as safety address unconditional requirements. Finally, economy and the environment can be seen as expenses that should be minimised over the life cycle, in principle dependent on the designer's skill in meeting the other requirements of the building. Economy and environmental performance can thus be regarded as resulting attributes. A better understanding of the interaction of these attributes and their dependence on the building and its service systems holds a potential for the improvement of the overall performance. Integrated Life Cycle Design, 'ILCD', incorporates both the whole life and the holistic perspectives. It is assumed that ILCD is an effective approach in the pursuit of improved overall performance.

Aim and approach

This work examines the application of ILCD, to Swedish concrete multi-dwelling buildings. The aim of the study is to look into methodological issues of ILCD and to present the fundamental attributes of dwelling buildings and how they relate to concrete as a structural material. Dwelling buildings were selected, as they are relatively well-defined and similar as regards performance requirements. The ILCD method is however generally applicable. Methods for prediction of two important life cycle attributes; the economy and energy use are examined and verified using comparisons of the real performance of some existing modern Swedish concrete dwelling buildings. Potential differences in life cycle performance are examined in parameter studies. A qualitative method to assess indoor environment in existing buildings is employed in one case.

Results and conclusions

The important attributes are briefly examined, and the significance of concrete as a structural material is discussed. When the multifunctional characteristics, such as fire safety, acoustics, strength and robustness in a broad sense are exploited,

concrete is a competitive and reliable structural material. The concluded is that concrete used for appropriate parts of the building can contribute to cost-effectiveness, and high overall lifetime quality of multi-dwelling buildings.

Life cycle costing, ‘LCC’, should be used to guide the design towards long-term cost-effectiveness. Roughly half the life cycle cost relates to the usage phase, and about three quarters of the operation costs are dependent on the design of the building. The most important operation costs refer to periodic maintenance, energy and care-taking. Adequate data for LCC calculations are available and used in facilities management and furthermore, there is detailed statistical cost information at hand for the entire stock of Swedish residential buildings distributed according to age, type of tenure, ownership and type of building. A simple spreadsheet tool was developed, in the thesis, for the calculation of the present value of and annual costs for multi-dwelling buildings and parameter studies were undertaken both on entire buildings and on the component level. A study on the life cycle cost of an existing building compared to an alternative design was conducted. This showed slightly higher production costs for the alternative with concrete frame (+1%) and brick façade (+3%) compared to a wooden frame with wood panel façade but looking at the life cycle costs this was balanced out by lower costs for periodic maintenance, insurance and energy. In this comparison, differences as regards functional criteria such as robustness, flexibility and acoustics were not taken into account.

Optimisation with regard to the global environment and resource use, throughout the life cycle of buildings was discussed and it was concluded that for the time being energy use for the operation of buildings is an adequate proxy parameter. A method to calculate socio-economic costs based on emissions to the air of CO_2, NO_x, SO_2, and VOCs generated by energy use was introduced. In the future, when reliable environmental product declarations will be available, LCA methodology may be used in the design phase to compare the environmental life cycle performance of different alternatives. Energy use during the operational phase will however then still be the key environmental issue and results from energy balance calculations will be used as input in the LCA.

It was verified that the energy use of a building can be estimated in the design phase with acceptable accuracy (+- 10%) with a suitable energy balance programme, in this case VIP+ (1994). Parameter studies showed the importance of the orientation of windows and the contribution of thermal storage and air tightness to energy efficiency. In residential buildings the free energy gains are relatively limited and the effect of thermal storage on annual costs is negligible. However, in the life cycle perspective the contribution is significant, in particular if environmental aspects are included, for instance using a socio-economic calculation. The savings with regard to the present value of life cycle costs is of a magnitude corresponding to differences in building costs for alternative types of building frames. The air tightness of the building shell, which is a typical feature of concrete exterior walls and roofs, influences the energy use of buildings with balanced ventilation, but not with mechanical exhaust ventilation. Air tightness is, however, important in all buildings in order to limit the risks of moisture problems in the climate shell and to achieve stable ventilation.

A simplified procedure for integrated lifecycle design has been outlined comprising software for energy balance calculations, acoustic design, LCC, LCA and multiple criteria decision-making. The tool for multiple criteria decision-making that can be used to optimise a design with regard not only to attributes that are measured quantitatively, but also qualitatively, was also outlined and tested.

This work indicates that design with integrated life cycle perspective could and should be further developed and introduced in the construction sector. The life cycle appraisal tools and data are already available and calculations can be done with reasonable effort and the results are reliable. Relatively small changes in the design may improve the overall lifetime quality of a building and the systematic ILCD approach in itself promotes life cycle quality.

1. INTRODUCTION

1.1 Background

The challenges of the building sector

The construction sector is sometimes referred to as the 40% sector indicating its great importance for society. Construction and the operation of houses has a tremendous impact on the economy and environment. Some figures referring to the EU: 11% of GNP, 30 million employees, 40% each of energy use, materials use and generation of waste (Sjöström, 2000). A substantial part thereof is related to the user phase, for instance 85% of the energy use of a modern Swedish dwelling building (Adalberth, 2000). Resource use and the global environment, indoor environment, economy and also social dimensions, commonly designated sustainability factors are thus to a considerable extent dependent on the efficiency of the construction industry and the life time quality of its products – the built environment. The European Commission presented in December 2001 a proposal for a directive on energy efficiency in buildings (EU, 2001) prompted by the fact that about 40% of the CO_2 emissions in Europe are attributable to the use of buildings. Environmental concern thus implies decreasing energy use in buildings, which, however, must be achieved while observing other quality aspects such as usability and a good indoor climate.

According to several investigations and commissions such as the *M4I, Movement for Innovation*, in the UK and *BKD* (2000) in Sweden, a 10-20% reduction in the total production cost and 10% in production time should be achieved for buildings in order to secure the affordability of housing. The average Swedish household spent 22% of its disposable income on housing in 1998 (SCB, 2000) and this share is increasing. Roughly half this cost relates to operating expenditures (Johansson and Öberg, 2001).

The building sector is, thus, faced with the challenge of both increasing its productivity and enhancing the long-term quality of its products.

The building - a multifunctional long-lived product

Buildings normally stand for a long period of time compared to many other products and the performance during the usage phase is particularly decisive for life cycle optimisation. Methods for life cycle appraisal are, however, rarely used in the design process today.

A building has a number of characteristics, in this work referred to as attributes, to meet the several different requirements that it is subject to. Some of the attributes are variables that can be expressed in performance classes, for instance sound insulation, while others, such as safety, address unconditional requirements regulated by norms. Finally, economy and the environment can be seen as expenses that should be minimised over the life cycle, in principle dependent on the designer's ability to meet the other requirements of the building. Economy and environmental performance can, thus, be regarded as resulting attributes. A better understanding of the interaction of these attributes and their dependence on the building and its service systems, holds a potential for the improvement of the overall performance

The requirements of a building refer to different stakeholders such as the producer, user, owner and the society. The interest of different stakeholders may or may not coincide. For example, energy efficient buildings are of public environmental and energy supply interest and they are also an interest of the user and the owner with regard to operation cost. There may, however, be no profit in energy efficiency for the producer. Non-coinciding interests are a building process related problem. One basic prerequisite to resolve this is knowledge of the life cycle perspective, of the interaction between attributes and how they relate to the design of the building and its service systems, items that will be addressed in this work. Another prerequisite is that the life cycle perspective is acknowledged and the long-term performance aspects and thus the interest of the owner, is linked to the designer and the producer. In other words, referring to the example of energy efficiency, if the client is aware of the quality in this respect, the producer can be rewarded accordingly. The introduction of energy declarations presented in the EU directive on energy performance of buildings (EU, 2001) is one practical tool to promote the acknowledgment of the life cycle issues, also highlighting this particular aspect with regard to the secondhand value of the building.

To safeguard the public interest as regards building products and thus buildings, the EU Building Product Directive states six essential requirements with a complementary demand on *durability*:

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health and the environment
4. Safety in use
5. Protection against noise
6. Energy economy and heat retention

Additional attributes that are deemed to be fundamental are:

Global environment and resource use. (Environment according to the EU requirement no. 3 refers only to the local environment of the building itself and requirement no. 6 covers only one – energy - out of several environmental and resource use related aspects)
Economy
Lifetime functionality/usability
Social aspects - Culture/Aesthetics

Sarja (2002, pp xvi, 28) presents a hierarchy where four main life cycle quality attributes for buildings; human conditions, financial costs, culture and ecology constitute the top level. Each main attribute is set up by several sub-attributes, which are supported by specific design objectives, including the requirements listed above.

The Integrated Life Cycle Design approach

Traditionally, the design and procurement process in the building sector aims at minimising production costs with regard to a set of minimum requirements related to norms and the more or less detailed specification of the client. Integrated Life Cycle Design, 'ILCD', incorporates both the whole life and the multifunctional perspectives. It is assumed that ILCD is an effective design approach in the pursuit of an enhanced overall performance of buildings. Sarja (2002, p4) explains the aim of Integrated Life Cycle Design as to *'fulfil the multiple requirements of users, owners and society in an optimised way during the entire life cycle of a building or other built facility'*.

The development of Swedish concrete multi-dwelling buildings

Concrete is a dominant structural material of modern multi-family dwelling buildings in Sweden. In situ, or prefabrication, or hybrid production methods are used and sometimes other structural materials, such as steel columns and beams are also incorporated. This variety provides a basis for competitive development as regard both the product and the production process.

Concrete is a multi-functional material providing several important features that can be to a greater or lesser extent utilized, such as load bearing capacity, fire protection, robustness in a broad sense, durability, thermal storage and sound insulation. Increased knowledge and awareness of these attributes, their correlation and the interaction between the building structure and the technical service systems in the whole life context, could improve the life cycle performance of new concrete buildings.

1.2 Aim and scope of the study

The objective of the doctoral project is to explore ways of enhancing the overall life cycle performance of Swedish concrete multi-dwelling buildings and to present this with a demonstration project. Integrated Life Cycle Design, 'ILCD' is expected to be a practicable approach for this aim. The purpose of this licentiate work is to establish a methodological background for life cycle optimisation and for this the applicability of ILCD is examined. By introducing ILCD it is anticipated that

- the awareness of the importance of a holistic life cycle design perspective will increase
- the understanding of the influence on life cycle performance of the design of the building will increase
- the process of optimisation with regard to several parameters that are measured either quantitatively or qualitatively will be supported.

The prime objective of this work is to examine the application of life cycle design methods and Integrated Life Cycle Design on Swedish concrete multi-dwelling buildings. The following specific research items are addressed:

I. To review the important attributes of a dwelling building
II. To determine the significance of concrete with regard to I above
III. To identify suitable life cycle appraisal methods
IV. To study and indicate the potential consequences on lifecycle cost-effectiveness and the environmental performance that could be achieved by application of the methods according to III above
V. To study and present how ILCD can be applied in the design of concrete multi-dwelling buildings

1.3 Approach and methodology

The work was set out with a survey on basic required attributes on multi-dwelling buildings and some considerations regarding their future development. The attributes, were reviewed by studying literature, norms and current practice and the significance of concrete as a structural material was analysed and presented for each aspect.

Methods for life cycle appraisal of costs and environmental performance and the input data required for predictions were reviewed by studying the literature and statistics. For indoor climate, a qualitative method to assess the performance of the finished building was examined as there are no agreed prediction methods as regard to this attribute. The applicability of the methods was studied by comparisons of results from calculations with measured data on life cycle costs, energy use and thermal comfort. Data from actual buildings was collected in field studies on selected modern Swedish concrete dwelling buildings. The field studies comprised production costs, operation costs, energy use for space heating and hot water, household electricity and a questionnaire survey to assess indoor climate.

Parameter studies were conducted on the life cycle design tools verified and adapted by the field studies on life cycle costs, energy use with related environmental consequences and thermal comfort. Alternative design solutions were evaluated to indicate the potentials of the life cycle design approach as regards improving of the life cycle performance of concrete dwelling buildings.

The ILCD concept was examined by studying the literature and standards. A simplified ILCD tool kit was outlined, covering key attributes such as life cycle cost and energy use and including commercially available software as well as spread sheet tools that were specifically developed in the project.

1.4 Contents and outline of the thesis

The scope of ILCD is by definition broad covering fundamental attributes of dwelling buildings. The scope of the thesis is to explore the application of ILCD, but the aim is also to define a background for this by examining the fundamental attributes of concrete multi-dwelling buildings. The study thus spans from technical characteristics of concrete dwelling buildings over methodological issues on life cycle performance prediction and optimisation to the practical application of methods for ILCD.

This introductory chapter presents a background to the challenges facing the building sector as regards to sustainable development and the context of this licentiate work. The principal research questions are defined and the research methods are presented.

Chapter 2 briefly presents current Swedish practice with regard to concrete structural systems and technical service systems for multi-dwelling buildings.

Chapter 3 gives a review of the fundamental attributes of dwelling buildings and their mutual interaction, the dependence on the building frame and the technical service systems. The significance of the concrete building frame is explored for each attribute.

Chapter 4 introduces the methodology of life cycle appraisal and multiple criteria decision-making and optimisation, which are applied in chapters 5 to 8.

Chapters 5 and 6 present detailed studies on methods for estimation and assessment with life cycle performance: Prediction tools and input data for calculations with regard to economy (Life cycle cost) and energy use, are surveyed, adapted and verified for concrete multi-dwelling buildings. The potential effects of different designs are explored through the application of the prediction tools in parameter studies.

Chapter 7 presents the application of a qualitative method to assess indoor environments and parameter study on indoor temperatures.

Chapter 8 gives an example of the application of ILCD on Swedish multi-dwelling buildings and outlines a simplified method for multi-attribute decision-making.

Chapter 9 discusses the findings of the study, focusing on the introduction of ILCD in practice

The thesis ends with outlines of future work in Chapter 10 and conclusions in Chapter 11.

2 TECHNOLOGY OF MODERN SWEDISH MULTI-DWELLING BUILDINGS

2.1 Brief overview of structural systems in modern Swedish concrete dwelling buildings.

In situ cast concrete slab blocks with curtain wall façades

In situ cast concrete frames for residential buildings are normally produced either with tunnel forms or in combination with prefabricated floor slabs and/or wall units. The thickness of the concrete is typically 200 to 250 mm, allowing spans up to 8 m in floor slabs and 160 to 220 mm in walls. Other layouts adopted from office buildings, such as column slab layouts, are also used. The 'curtain wall' façades are prefabricated or built on site with studs of sheet steel or wood and cladding of bricks or rendering on mineral wool. The structural layout is presented in Figure 2.1 A 'traditional' and 'alternative'.

The cast in-situ concrete frame has been the dominating structural concept for multi-dwellings buildings in Sweden during the last two decades. The tradition and skill among Swedish contractors can explain this. Important current development trends are the introduction of self-desiccating concrete to speed up the production cycle and self-compacting concrete to increase productivity and improve working conditions on site. Post-tensioning has also been introduced to increase the floor span in order to improve flexibility. Furthermore, special frame production contractors have emerged in the market.

The Swedish Ready Mixed Concrete Association has compiled a comprehensive overview covering both production and functional aspects with regard to cast in situ frames, 'The Concrete Bank' (SFF, 2000).

A precast concrete structure with load carrying sandwich façade elements

A main feature of the precast frame is the use of the prestressing technique in floor elements, which can be either hollow core slabs or massive elements. Hollow core slabs with sections 1200x200 or1200x265 mm allows spans up to 13 m, see Figure 2.1 B. The concrete used is earth moist, of strength class C45-C50, and the elements are produced using the extrusion technique, typically on 100 m long beds. When sufficient concrete strength for the release of the pre-stress has been achieved, the slabs are sawn into specified lengths. The joints between hollow core slabs are filled on site with concrete. Usually a topping of self-levelling compound is applied on the slabs. Alternatively, a raised floor, for instance parquet on joists, is used. The latter solution allows for installations to be placed in the floors. The exterior walls usually consist of sandwich wall panels with an exterior, 70-80 mm concrete layer, usually painted in the factory with a texture similar to rendering, a 100-150 mm thermal insulation layer and an internal 100-150 mm load carrying concrete layer.

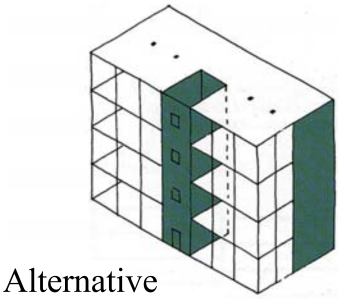
Systems with a short span, reinforced massive floor elements and load carrying internal walls in a layout according to the in situ cast concrete in Figure

2.1 A ‘traditional’, are also used. Such elements are produced either individually on horizontal tables, or as packages, vertically in ‘battery’ forms. For most non-tensioned elements including sandwich wall panels, concrete of strength classes C30 to C40 is used. This is primarily not motivated by need for strength but to allow adequate form stripping time.

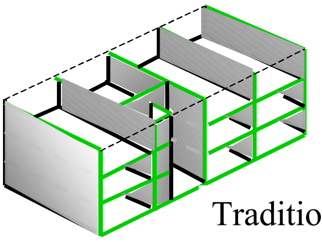
In Sweden, the structural design of the precast frame is performed by or at least managed by the precast producer, who is also normally responsible for the transportation of elements and erection on site. Thus the precast producer has the overall responsibility for the building frame.

Development trends in the precast sector are, for instance, ‘joint free’ façades for aesthetical reasons and ‘package concepts’ incorporating complete building frames including installations.

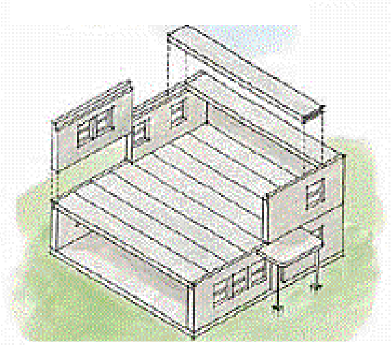
A. Cast in situ



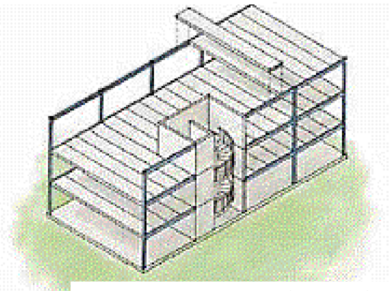
Alternative
Column/slab (Mushroom constr.)



Traditional.
Slab block



B. Precast concrete
Sandwich facades +
hollow core floors



C. Concrete and Steel composite
Steel columns and beams +
concrete floors

Figure 2.1 Outlines of common structural frame systems.
A - Alternative with permission from the Swedish Ready Mixed Concrete Association.
A - Traditional. Sketch by the author
B,C with permission from Skanska Prefab AB, Malmö, Sweden

Concrete and steel composite structures
The steel and concrete composite structures were introduced at the end of the 1980s, copying the concept from the office building sector. The structure normally consists of steel columns of hot rolled rectangular hollow or H-section and steel beams of hot rolled H or special welded profiles. Prestressed concrete hollow core slabs, as described above, massive concrete floor slabs with in-situ concrete overlay or lightweight concrete floor elements are used as slabs. For stabilisation, prefabricated, concrete stair enclosures are often used. The façade is a curtain wall similar to that of the in-situ concrete frame, described above, and the interior walls are lightweight structures made of plasterboards on sheet steel studs apart from the stabilising concrete stair enclosures. Compare Figure 2.1 C.

Light weight aggregate concrete
Light weight aggregate concrete, either as expanded clay aggregate concrete blocks or elements, or as autoclaved aerated concrete panel walls or block walls, are used in combination with cast in-situ concrete slabs, precast concrete slabs or in some cases with expanded clay aggregate floor elements. Lightweight concrete components for exterior walls may be homogenous or of sandwich-type with a layer of insulation between internal and external layers of lightweight concrete.

2.2 Brief overview of technical services systems in Swedish multi-dwelling buildings

The heating and ventilation systems in combination with the building structure and the building envelope set the indoor climate conditions. For new multi-dwelling buildings there are several systems for heating and ventilation available.

According to SCB (2000), in 1997, 72% of the heated floor area in Swedish multi-dwelling buildings was supplied by district heating with the corresponding share 88% in new production. Other energy sources are natural gas or oil. In the latter case a boiler supplies one or several buildings with heat. Electricity is also used for heating in some cases. Hot water radiators normally distribute the space heating, but floor heating, or air heating, have also become technically feasible since highly insulated windows do not require a closely placed heat source to avoid condensation on their inner surface.

Table 2.1 Overview of ventilation systems.

Ventilation system	Swedish denomination	Relative production cost
Natural	S	1,5*
Mechanical exhaust ventilation	F	1*
Mechanical supply and exhaust	FT	4,3*
Mechanical supply and exhaust ventilation with heat exchange	FTX	4,9*

** The material and installation costs for ducts and apparatus including necessary building measures. According to Hjertén, Mattson and Westholm (1996)*

The ventilation systems used in residential buildings are listed in Table 2.1, and in Figure 2.2 the market share during different periods is displayed. Note that the market share for FT and FTX systems was boosted in the early 1970s, which was due to increased energy prices and public subsidies for the installation of heat exchangers and heat pumps following the oil crisis.

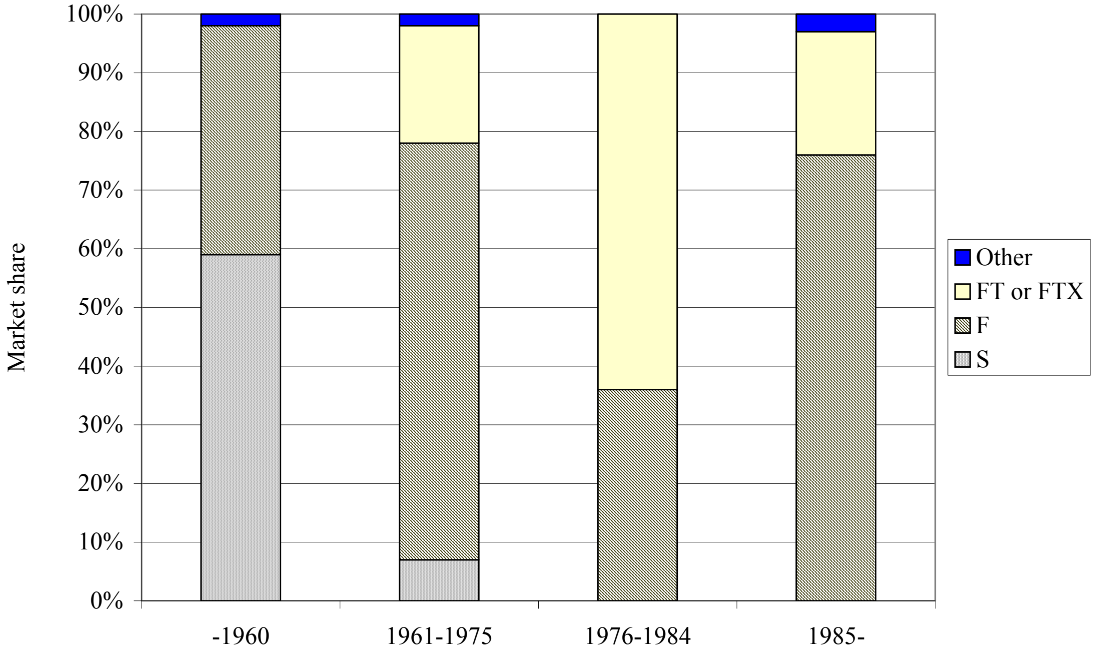


Figure 2.2 Distribution of ventilation systems in multi-dwelling buildings in Stockholm distributed by age of building. (Engvall and Norrby, 1992).
FT or FTX = Mechanical exhaust and supply air, F = Mechanical exhaust air, S = Natural ventilation

The natural ventilation system ('S') uses the thermal driving force, whereby the used air leaves the building through the ceiling via exhaust ducts and the fresh air is brought in through valves in the exterior walls, or through air leaks. Natural ventilation is very quiet, no space is needed for apparatus and the operating and maintenance costs are negligible. The exhaust ducts must, however, be 3 times the size of mechanical systems. The main negative aspect is the difficulty of controlling the ventilation rate. In cold conditions, the ventilation rate may become too high which implies waste of heating energy, while in hot weather, the thermal driving force is not strong enough for sufficient air exchange. Differences in air tightness in various parts of the building may also lead to inadequate ventilation. There are a number ways of modifying natural ventilation in order to improve the performance, such as temperature controlled inlets ('bimetal'), a wind device on top of the exhaust duct or inlets via snorkels. There is no rational way of obtaining heat recovery with natural ventilation, which of course is a drawback, since ventilation represents a major part of the energy balance of a building. The choice of natural ventilation in the current production of multi-dwelling buildings is restricted to experimental housing, compare Figure 2.2.

By using mechanical exhaust ventilation (‘F’), the thermal driving force is replaced by fans in exhaust ducts, normally with inlets in the bathroom and the kitchen, where the need for ventilation is great and where the noise from the inlet is the least disturbing. By adjusting the inlet valves, the ventilation rate can be individually controlled. By shutting a valve, however, the airflow through the remaining open valves may increase to uncomfortable levels as the balance between exhaust and intake air is constant. Special pressure controlled exhaust fans may prevent this effect. In order to improve the energy balance in a building with mechanical exhaust ventilation, it can be equipped with a heat pump that recovers energy for hot water supply. One major advantage of this system is that the building is exposed to a constant under-pressure, which ensures safe moisture conditions in the climate shell, since no damp inside air will penetrate it by convection. The need for maintenance, and thus the operating cost of the system, is also comparably low. As indicated in Figure 2.3, below, the thermal comfort in buildings with F systems is regarded inferior to buildings equipped with FT systems. Cold draughts from inlet valves and air-leaks in the climate shell might explain this. Sufficient air-tightness of the building and location of the inlets behind radiators in order to avoid the inconvenience of cold draughts are prerequisites to obtain good thermal comfort with F-systems. As regards air quality the perceived difference between, the F and FT systems is insignificant, according to Engvall and Norrby, (1992). Compare Figure 2.3, below.

Mechanical supply and exhaust ventilation (‘FT’ or ‘FTX’) adds the possibility of being able to condition the supply air by heating, cooling, or the powerful filtering of particles. The FT system needs considerably more space for the apparatus and the control system is more complicated compared to the other systems. Increased complexity implies higher maintenance efforts. Special attention must be paid to the supply air part of the system in order to prevent the risk of polluting the incoming air due to, for instance, dirty filters. The system provides good opportunities for heat recovery. The ‘FTX’-system usually uses simple plate heat exchangers between the exhaust and supply air. The FT-system may use a heat pump to recover energy from the exhaust air for hot water production or to heat supply air.

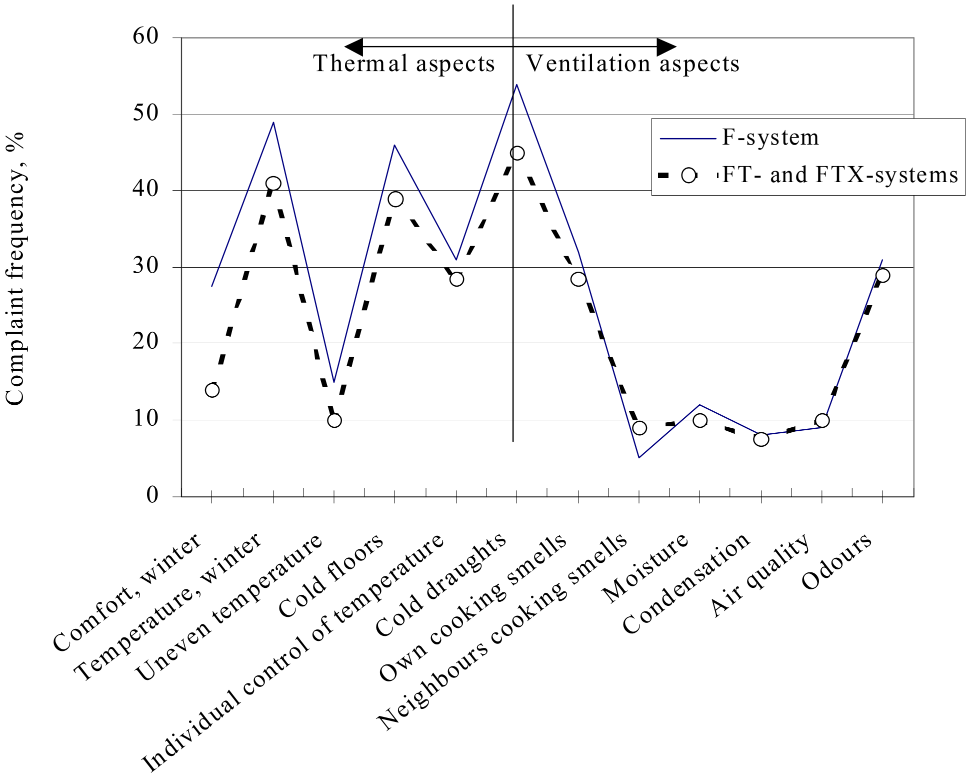


Figure 2.3 Perceived indoor climate quality distributed by type of ventilation system in multi-dwelling buildings constructed after 1985 (Engvall and Norrby, 1992).

The service systems constitute a large part of the overall production and maintenance efforts in residential buildings. The physical fitting of systems into the building needs careful consideration to facilitate maintenance and not to limit the flexibility regarding use of the building. The function of the service systems and their interaction with the building and the users are of utmost importance for user satisfaction and building performance as regards aspects like the indoor climate, life cycle economy and energy use.

3. ESSENTIAL ATTRIBUTES OF A BUILDING AND THEIR INTERACTION

3.1 General

To design for the optimal long-term performance of a building, its fundamental properties must be addressed, quantified and their relative importance estimated. Furthermore, the interaction between these properties and their dependence on the building frame and the technical services systems, must be considered. This chapter discusses the important characteristics, here referred to as attributes, of multi-dwelling buildings, their interaction, the significance of concrete and in some cases methods to assess the performance in question.

To define the direct public interest as regards building products, and thus buildings, the EU Building Product Directive states six essential requirements:

1. *Mechanical resistance and stability*
2. *Safety in case of fire*
3. *Hygiene, health and the environment*
4. *Safety in use*
5. *Protection against noise*
6. *Energy economy and heat retention*

A *durability* requirement follows automatically as it is stated that the requirements must: 'subject to normal maintenance, be satisfied for an economically reasonable working life'. The directive is presented in more detail in Appendix A.

Additional attributes that are deemed to be fundamental are:

Global environment and resource use. Environment according to the EU requirement no. 3 refers only to the local environment of the building itself and requirement no. 6 covers only one out of several environmental and resource use related aspects.

Economy

Lifetime functionality/usability

Social aspects - Culture/Aesthetics

In Figure 3.1, the attributes that are deemed to be of fundamental importance for a multi-dwelling building are listed and their interaction indicated. This illustrates the complexity of functional interaction and hence the difficulty of optimisation. As indicated in Figure 3.1, requirements may be contradictory or coincide from a technical point of view, but that may also be the case between stakeholders. For example, energy efficient buildings are of public environmental and energy supply interest and they are also an interest of the user and the owner as regards operational cost. There may, however, be no benefit in it for the producer. This is a building process related problem. One basic prerequisite to resolve it is understanding and acknowledging of the life cycle perspective, the interaction between attributes and how they relate to the design of the building and its service systems. Another example is if market energy prices do not reflect the true scarceness of this resource, investments for energy saving measures are wanted by society, but not appreciated by the investor.

Mechanical resistance / stability												
Safety in case of fire	+											
Hygiene, health (indoor climate)	+-	O										
Safety in use	+	+	+									
Acoustics	+-	+	+	O								
Energy economy	+	O	+-	O	+-							
Durability	+	+	+	+	O	+						
Global environment	+-	+-	+-	O	+-	+	+					
Life cycle cost	+-	-	+-	-	-	+	+	+-				
Lifetime functionality/usability	+-	-	+-	O	+-	+-	+-	+	+			
Social dimensions/aesthetics	+-	O	O	O	-	+-	+-	+-	-	+-		
Robustness	+	+	+	+	+-	+-	+	+	+	+	+-	
-: Improvement of one => impairment of the other. *O: No significant correlation* *+: Improvement of one => improvement of the other* *+-: Can work either way*	Mechanical	Safety in case of fire	Hygiene, health …..	Safety in use	Acoustic	Energy economy	Durability	Global environment	Life cycle cost	Lifetime functionality/usab.	Soc. dimensions/aesthetics	Robustness

Figure 3.1 Tentative system of fundamental attributes and their interaction

3.2 Mechanical resistance

Mechanical resistance and stability are requirements that are fixed by regulations. In terms of integrated design and optimisation they are, thus, more or less unconditional screening attributes. An added value can however be attached to materials and structural designs that contains inherent margins with regard to load bearing capacity or durability, see further section 3.13 on robustness. The load bearing behaviour of reinforced concrete structures in general is characterised by

- ductile behaviour where failures are proceeded by substantial deformations and cracking
- the proportion between imposed load and total load that is low due to the high density of concrete
- the difference between load in the serviceability limit state and the ultimate limit state is small due to the high density of concrete

For a 250 mm concrete slab in a dwelling building designed according to the European design standards, 'Eurocodes' the relation between imposed and total load with partial safety coefficients for the ultimate limit state is 0,20. The proportion between the serviceability limit state and the ultimate limit state for the same slab is 0,70. This implies that a concrete structure is robust with regard to load changes or accidental loads.

Changes in an existing structure such as new openings are often possible. In a two way reinforced slab loads can often be redistributed and in one way pretensioned slabs a large opening can be catered for using steel yokes to carry the cut slab. The high density of concrete may, however, also be a disadvantage. Typically lighter structural materials are often selected when an existing building is going to be extended upwards if the building was not originally designed for that load situation. Table 3.1 shows normal spans for dwelling buildings with different types of concrete frames.

Table 3.1 Normal thickness and spans for concrete slabs for dwelling buildings

Type	Thickness (mm)	Normal span (m)	Reference
Prestressed hollow core slab	200	5-9	(BE, 2001)
Prestressed hollow core slab	270	6-13	(BE, 2001)
Floor slab	200-300	3-6	(BE, 2001)
Pretensioned floor slab	200-300	6-10	(BE, 2001)
In situ cast slab	200-300	3-10*	(SFF, 2000)
In situ cast slab, post tensioned	200-300	8-15*	(SFF, 2000)

** Dependent on joint spacing and bearing*

In the typical in situ cast concrete dwelling building, no specific measures to ensure stability are necessary. Precast concrete frames use tie bars that follow the edge of a floor to secure diaphragm action so that transversal loads can be conveyed to wall diaphragms. These diaphragms also secure stability in case of accidental loads, such as the loss of a segment of the structure by an explosion.

3.3 Fire safety

There are three levels of safety in a building according to the building regulations (Boverket, 1998). The highest safety level, Br 1, is applicable for three storey buildings and higher. The fire resistance classification of a structure is determined by: R (load carrying capacity), E (integrity) and I (insulation) followed by the length of time, expressed in minutes, that the component would withstand a standard fire. A building is divided into fire cells for the confinement of fires. In a residential building a fire cell is typically one flat. A structure separating fire cells in a residential building with fire safety class Br1 must have a fire resistance of not less than EI 60. Façades are also regarded as being part of the fire cell confinement. For the load carrying capacity of structural and stabilising structures, the requirement is R60, R90 or R120 for residential buildings depending on the number of floors in the building and the type of structure. A REI 120 concrete structure is 180 mm thick and a REI 240 is 300 mm thick.

Fire safety in a building is dependent on the

- ability to keep a fire in a confined area /EI/
- fire resistance of load carrying and stabilising structures /R/
- behaviour of the materials regarding ignition, combustibility and build-up of smoke
- escape possibilities
- fire alarm systems
- availability of active fire protection devices such as sprinklers. (Such systems are normally not used in residential buildings)

3.4 Indoor climate – Hygiene and health

In average 65% of our time is spent at home and an additional 20% is spent inside other buildings. It is acknowledged that comfort, health and mental capacity are closely related to the indoor climate and that the indoor climate can be, partly, but not fully, described in technically quantifiable terms. Calculations and predictions can be made regarding moisture conditions, thermal comfort and air exchanges related to ventilation and air leaks in the climate shell. The overall indoor climate quality can be assessed by questionnaires to the tenants, which by definition implies that it is not a direct design instrument. However, a questionnaire is a way of collecting feedback, which should be used to guide the design with respect to the quality of the indoor climate in future projects. This section provides an overview of indoor climatic aspects.

Temperature

The operative temperature is dependent on temperatures in the air and on surfaces in combination with air velocity. In the Swedish building regulations (Boverket, 1998), the minimum operative temperature is set at 18°C in residential space with the exception of 20°C in bathrooms. The surface temperatures may vary between 16°C and 27°C. The maximum permitted air velocity is 0,15 m/s during the heating period and otherwise 0,25 m/s. Materials exposed to the indoor environment stabilize the temperature according to their capacity to absorb and release heat as discussed in Section 3.7. In dwelling buildings, the two main sources of excess heat is solar radiation through windows and household appliances. Depending on the orientation of windows, this energy can decrease the required space heating as discussed in Section 3.7 below. Optimised solar gains during the heating season, however, contradict optimised thermal comfort during summer. The active thermal mass in the building evens out temperatures, which is discussed in Chapter 7.

Indoor air quality, IAQ

The concentration of different species and particles in the indoor air and their connection with sources is relatively well known. Pollution sources are

- biological such as human exhalations, mite and mould
- outside air pollution
- emissions from materials

The measuring methods for quantifying concentrations of species in the air, expressed in µg/m^3, as well as emissions from materials, expressed in µg/m^{2}h, are reliable. There is, however, a lack of knowledge about their effect on humans. There are recommendations in the building regulations and in other IAQ assessment systems as regards the maximum contents of TVOC, Total Volatile Organic Compounds, but it is acknowledged that this is only an indicator of the amplitude of emissions and that it says nothing about the harmfulness of the particular species in question. In the Swedish building regulations, there is also a requirement on minimum air exchange volumes for residential buildings defined as 0,35 l/s,m^2 floor area.

Several investigations regarding primary emissions from concrete, for instance Wengholt (1995), confirm that there are only small and a few weeks after casting, negligible self-emissions from concrete. This is the case also in concrete with high dosages of admixtures or additions. Sick building symptoms in connection with concrete structures primarily relate to secondary emissions from floors with bonded flooring systems, see further below.

Humidity

The indoor air humidity affects our experience of indoor comfort, the durability of materials and biological risks, such as mould growth. The humidity is normally greater in new buildings, because of the moisture content in new materials and the moist climatic conditions on the building site.

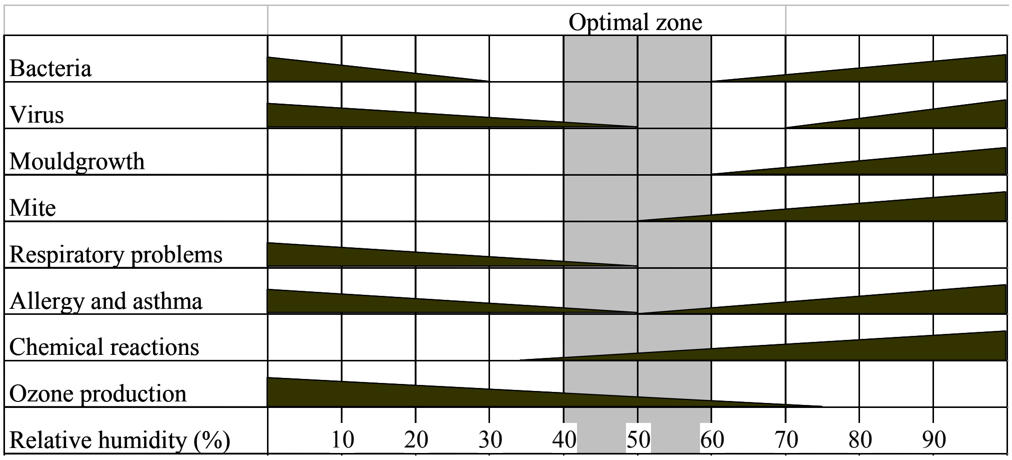


Figure 3.2 Optimal indoor relative humidity according to Hjertén, Mattson and Westholm (1996). Increased height on triangles => increased risk

A majority of the moisture related problems in buildings could be attributed to neglecting the high moisture level in a new building. The humidity will reach a balanced level a certain time after construction, depending on indoor moisture sources and ventilation. There is also a seasonal variation linked to the outdoor conditions. Variations in humidity are to a certain extent balanced by the hygroscopic activity of building materials. Materials also have different durability as regards moisture exposure. Typically, durability is reduced when moisture content is increased. The humidity is an important indirect parameter with regard to sick building problems. In Figure 3.2, an optimal or safe zone for relative humidity has been proposed. Adan (1994) discusses fungal growth on indoor surfaces and establishes that humidity is the decisive factor. Adan shows that relatively short periods of high humidity on surfaces provide conditions for fungal growth, even though the average humidity remains low. Adan also indicates control strategies with a surface temperature criterion and for transient conditions such as kitchens and bathrooms a 'time of wetness' criterion.

Air tightness

Air tightness between different flats and over the climate shell is important for various reasons. The shielding function with regard to energy, fire, noise and odours is directly dependent on air tightness. An air tight climate shell is thus a prerequisite in order to limit energy use for heating, to achieve an even ventilation rate in different rooms and finally, to avoid the risks of condensation of moist indoor air in the exterior wall or roof. Condensation often leads to decreased function of insulation material and mould problems in organic materials. Above all, buildings with balanced ventilation, but also natural ventilation, are sensitive from this point of view, because of the risk of interior excess pressure in certain parts of the building.

In heavy structures, such as concrete outer walls, no specific measures need to be taken as regards air tightness and the material is not susceptible to any deterioration due to moisture. Wall to floor connections, window and door fixtures and movement joints are simple to design, produce and maintain. In lightweight structures, sheets of plastic foil ensure the air tightness and the moisture shield. Special care should be taken as regards connections and the plastic foil should be protected from mechanical damage during the user phase. The long-term durability of plastic foil has also been questioned.

3.5 The significance of moisture

As discussed in Section 3.4, moisture and humidity are important as regards degradation of materials and, thus, both relevant to indoor climate and economy. In this respect the behaviour of building structures is dependent both on material characteristics and the design and it is a problem related to both the production and to the use of the building.

Fresh concrete contains water that needs to be dried out, however, the material in itself is not susceptible to damage from moisture, either during production or use. If a concrete floor has not been sufficiently dried out, the moist alkaline environment may decompose the adhesive layer under the flooring material, by hydrolysis, which may lead to the emission of substances into the indoor air. Sjöberg (2001) concludes that both moisture and alkalinity are needed to trigger this reaction. During the 90s self-desiccating concretes were introduced, in Sweden, reducing the drying times of fresh concrete considerably. Self-desiccating concrete normally contains a large proportion of cement and relatively high doses of water-reducing agents. It has been discussed whether the increased alkalinity of these cement rich concretes may increase the risk of emissions. Experience shows that the problem is related to the additional water from the adhesive that the self-desiccating concrete is not capable of buffering. This might induce a critical combination of alkalinity and moisture. Solutions to this problem are either to apply a low alkali screed on the concrete or to use an adhesive that does not add water to eliminate either the alkalinity or the moisture condition. An adequate computer tool including databases for the moisture design of concrete structures, TorkaS (1999), is available as well as reliable methods to measure the moisture content, in a floor before the application of adhesives and carpets.

The climate shell of the building, which is exposed to moisture or water, need particular consideration. The bottom, or basement floor of a multi-dwelling building, is normally a slab on ground. This is a moisture safe design provided there is thermal insulation and adequate drainage below the concrete slab. An outdoor air ventilated crawl space is more sensitive since it is highly humid especially during the summer. Organic materials should thus be avoided in the crawl space and the floor above should be consistently air tight in case of mould growth inside the crawl space.

Increased insulation in ventilated roofs may have led to low temperatures that must also be considered carefully to avoid condensation. A typical conflict between architectural and building physical ambitions is the horizontal roof, which is technically risky as regards water tightness and makes heated rainwater drainage ducts necessary in cold climates.

The robustness of the exterior wall with regard to water is crucial. Repairs are expensive, wetting decreases thermal insulation and any degradation such as mould growth is very likely to affect the indoor air.

3.6 Acoustics

The important sources for noise disturbances are:

- Noise caused by human activity in other apartments or common areas inside the building such as staircases and elevators
- Noise from technical systems inside the building
- Noise from the outside
- Noise from inside the apartment

Figure 3.3, shows the average complaint distribution regarding noise in Swedish residential buildings built from 1985 to 1990 (Engvall and Norrby, 1992).

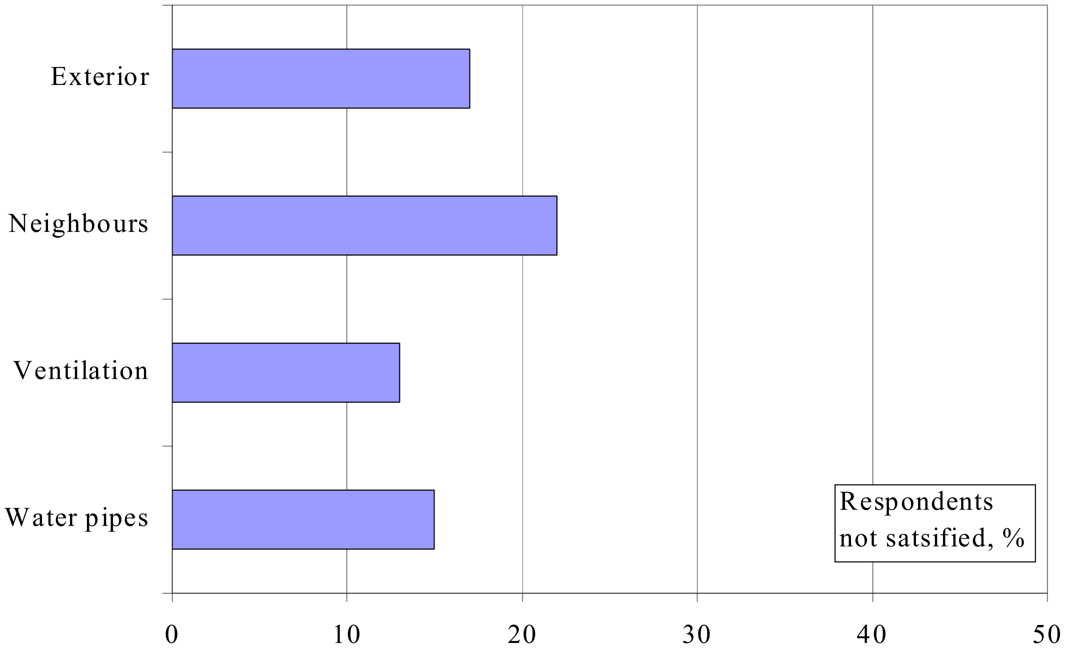


Figure 3.3 Noise complaint distributions in modern Swedish multi-dwelling buildings according to Engvall and Norrby (1992).

The current Swedish building regulations, BBR99 (Boverket, 1998), classify sound insulation in four levels, A to D, to which specific requirements on sound reduction, over the enveloping surfaces apply. According to BBR99, the next lowest sound level class, C, is the minimum quality level for new residential buildings. Table 3.2 presents requirements on sound insulation and examples.

Studies indicate that sound insulation is a very important quality aspect regarding residential buildings. An investigation carried out by the Swedish National Building Research Foundation indicated that 60% of the respondents were willing to pay 5%, and 40% were willing to pay 10% more for a quieter apartment. Sound class B is regarded as a minimum standard for good quality dwelling buildings according to Åkerlöf (2001).

The transport of sound inside a building depends on both the direct airborne sound through the partitioning structures, the impact sound insulation, the flanking transmission, which is indirect sound transmission through the surrounding constructions, ducts for technical services and finally the disposition and sizes of rooms. The acoustic performance is determined both by the design and the execution. Small deficiencies such as cracks or holes in structures may ruin the acoustic insulation.

Table 3.2 Sound insulation requirements according to BBR99 and examples of perceived noise from neighbours according to Åkerlöf (2001, pp 22-23)

	Airborne sound insulation*	Example	Impact sound pressure levels*	Example
Class of sound insulation	Min. sound reduction index R_w** (dB)	Normal TV or audio equipment	Max. impact sound pressure levels L_n** (dB)	Children playing
A	60	Not heard	50	Not heard
B	56	Could be heard	54	Could be heard
C	52	Could be heard	58	Could be heard
D	48	Heard	62	Could be heard

** Between flat and surroundings*

*** For classes A and B and recommended in class C: the weighted sound reduction index* $R'_w + C_{50\text{-}3150}$ *and impact sound pressure levels* $L'_n + C_{1,50\text{-}2500}$ *should be used. The correction factors* $C_{50\text{-}3150}$ *and* $C_{1,50\text{-}2500}$ *are dependent on type of structure. A massive concrete wall typically has* $C_{50\text{-}3150} = 1$ *and a light wall* $C_{50\text{-}3150} = 4$

Because of the complexity behind acoustic performance it is not possible to determine the precise acoustic quality of a building on the basis of acoustic data for the single components. Additional layers, connections, the building layout and also the relation as regards the density and stiffness between adjoining structures have to be considered. Acoustic design may be based on a series of international standards. These standards, EN ISO 140 and EN 12354, have been developed based on theoretical models as well as common practical experience. A computer program based on these standards, BASTIAN® (1996), can be used in early design stages for the acoustical evaluation of alternative technical solutions. The program is furnished with a database comprising necessary acoustic input data for normal cast in situ as well as precast element concrete structures and typical flooring materials.

Acoustic properties relevant for exterior walls are the direct sound reduction related to for instance noise from traffic, but also the flanking transmission potentially conveying sound between different rooms in the building. In a concrete exterior wall it is normally windows and ventilation openings and the design and execution of the connecting details, that are critical for the direct sound reduction. The flanking transmission can be taken care of by a proper detailing of the connections between the façade, interior walls and floors. The BASTIAN® (1996), program can be used also for the acoustic design of exterior walls.

Data on acoustic performance of the individual structural element can be obtained from handbooks, such as Åkerlöf (2001) or Wikells (2000). Note that it is not possible to determine the precise final acoustic quality of a building with data for individual components. Hence the values given only indicate expected levels that sometimes underestimate the performance of the component in the finished building. It is, however, possible to achieve reasonable approximations for buildings, conforming to type cases, based on experience from measurements in such buildings and some adapted acoustic formulas. The Swedish Ready Mixed Concrete Association has developed a computer tool in the 'The Concrete Bank' (SFF, 2000) that can be used for the approximate acoustical evaluation of concrete frames. The cases available are slab blocks or column slab structure as shown in Figure 2.1 A. Figures 3.4 and 3.5 show the potential acoustic class of a building calculated by 'The Concrete Bank'. Airborne sound reduction /R/ and impact sound reduction /L/ are calculated with the following semi-empirical formulas according to Ljunggren (2000)

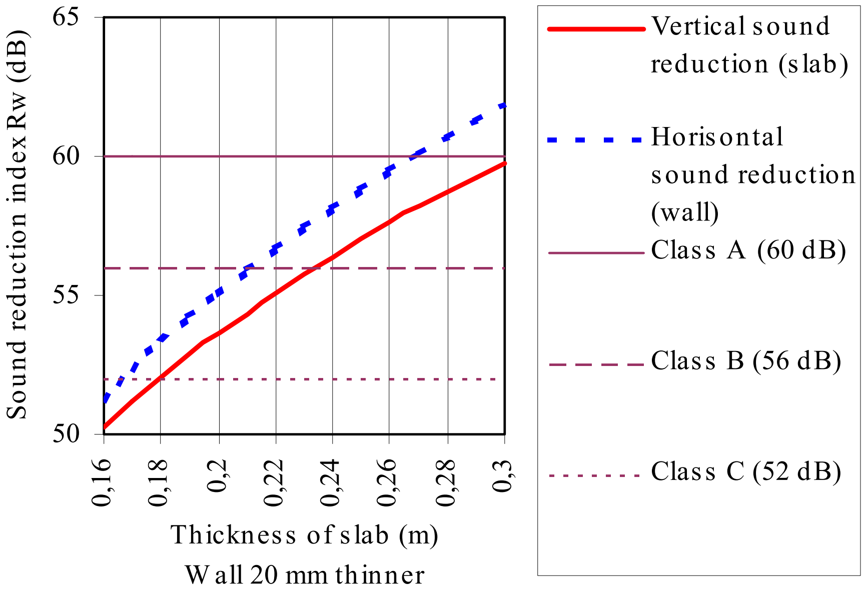


Figure 3.4 Airborn sound reduction index for a concrete slab block frame

$$R_{wv}=53{,}2+35*LOG(h/0{,}16)-10*LOG(a/16)+10*LOG(w/12)-2{,}5+0{,}5-s*1-f_l*2 \tag{3.1}$$

$$R_w=54{,}1+35*LOG((h-0{,}02)/0{,}16)-10*LOG(\sqrt{a}*H/16)+10*LOG(w/12)-2{,}5-f_l \tag{3.2}$$

$$L=52-Rv+3(7-f_2)+56 \tag{3.3}$$

where

R_{wv} = Airborne sound reduction index through floor – vertical (dB)
R_{wh} = Airborne sound reduction index through wall - horizontal (dB)

L = Impact sound pressure level (dB)
h = thickness of slab or wall (m)
H = height room (m)
a = area of room (m^2)
w = width of building (m)
s = factor to compensate when floor spans < 4m
f_1 = factor for floor covering class with regard to airborne sound insulation
f_2 = factor for floor covering class with regard to impact sound

In the example calculated in Figures 3.4 and 3.5, the floor is covered with a plastic carpet or similar placed on acoustic foil corresponding to acoustic floor class 7 according to Swedish standard SS 02 52 67. Area of room = 35 m^2, width of building 15m.

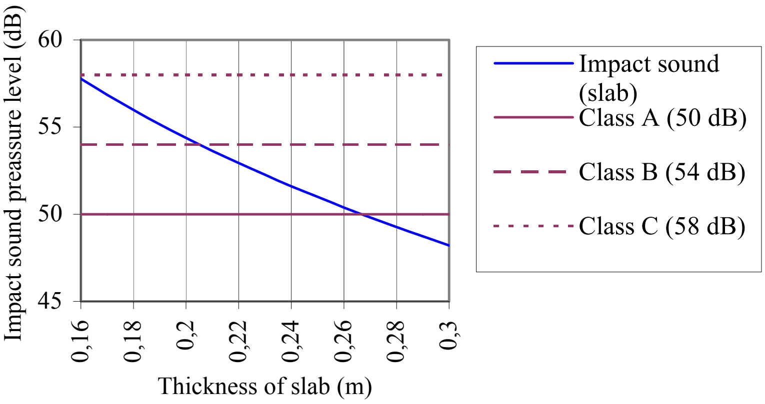


Figure 3.5 Impact sound reduction for a concrete slab block frame

The column slab type of structure is very advantageous as regards both airborne and impact sound insulation. The algorithm for airborne sound reduction index through a floor in a column slab structure corresponding to (1) for the slab block structure above is, according to Ljungren (2000):

$$R_{wv} = 63{,}5+35*LOG(h/0{,}16)-5*LOG(a/16)+5*LOG(tf/600)-f_1*2-2{,}5 \quad (3.4)$$

where

tf=total floor area (m^2) and other parameters as above

Thus, with an equivalent thickness of the slab, the column slab structure provides roughly one sound class better sound insulation than the slab block structure.

The advantages of concrete with regard to acoustics are related to the density and stiffness and the comparably simple and robust details of connections. The density is particularly important to reduce low frequency sound, for instance from traffic or modern audio equipment. The step from sound class C to B is comparably easy to obtain for traditional concrete residential buildings. The step from B to class A is obtainable, but requires more special considerations. The type of floor covering is very crucial as regards impact sound insulation. Complaints about noise in concrete buildings primarily relate to the deficient design of connections leading to flanking transmission and to floor coverings that do not subdue impact sound.

3.7 Energy use

3.7.1 General

Energy is used through all life cycle phases from the extraction of raw materials to demolition and recycling. The use of energy has both great environmental and economical implications. In order to form a relevant strategy for the reduction of energy consumption in buildings it is important to be aware of the relation between different phases in the life cycle, regarding energy use. Table 3.3 shows results from two studies, indicating that the user phase is dominant. Normally, multi-family residential buildings have a longer life cycle than 50 years, which emphasises the user phase even more.

Table 3.3 Energy use over a 50-year lifecycle for a multi-family residential concrete building in Helsingborg in southern Sweden, built in 1996, according to Adalberth (2000, paper 3, p 7) and for a similar theoretical building according to Björklund et al (1996)

	Adalberth		Björklund et al
	kWh/m^2	Share (%)	kWh/m^2
Production of materials and components	820	9	340
Transports of materials and components	30	-	
Building site	120	1	30
Use (heating, hot-water, light, other electricity)	7500	84	7640
Maintenance and repair	410	5	60
Demolition	< 10	-	14
Demolition material transport	20	-	

The discrepancy between the two studies presented in Table 3.3 with regard to energy used for production and maintenance is due to the fact that Björklund only considers materials and components related to a limited part of the building and only materials constituting frame and climate shell. Roof, foundation, technical service systems, fittings etc. are thus left out and it is therefore difficult to express these figures in terms of share.

3.7.2 Production phase

The energy use for the production of a building is distributed over extraction and production of fuel and electricity, extraction of raw materials, transport of raw materials and fuel, production of components, transport of components to the building site and the construction work. In the study by Björklund, referred to above, the total energy use for the production of different types of structural frames including in situ concrete or steel/concrete composite frame and precast concrete was mapped. The unit for comparison was 1 m^2 of the building area, 'cradle to gate', including a proportion of external and interior walls, but excluding the roof, foundations, service systems, surface materials and fittings. The calculated energy required for the production phase varied between 380 and 430 kWh/m^2 or approximately 20%. In the study by Adalberth (2000, paper 3, p 7), four different existing modern multi dwelling buildings comprising between 6 and 16 flats were examined including different structural frames, such as concrete/lightweight concrete, concrete, steel/concrete and timber. The energy use for production varied between 900 and 1260 kWh/m^2. In a comparative study presented in the same paper (p 12) with a timber frame and a theoretical cast in situ alternative for same building, the energy use was estimated at 1090 kWh/m^2 for the concrete and 1260 kWh/m^2 for the timber building. If the inherent energy is excluded, the corresponding figures were 750 kWh/m^2 for the concrete and 640 kWh/m^2 for the timber building. In the whole life perspective with an operational phase requiring approximately 7500 kWh/m^2, the difference between the energy

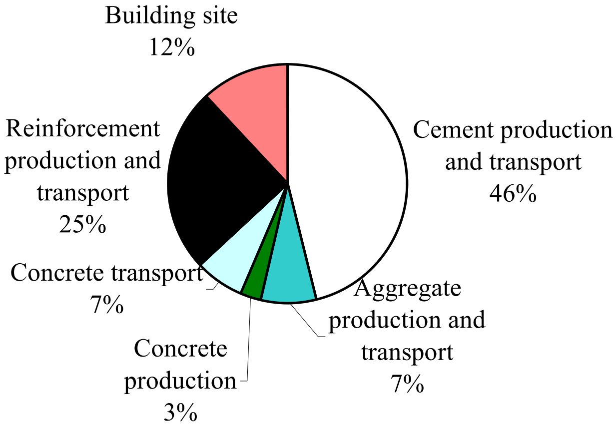


Figure 3.6. Distribution of energy use for the production of reinforced concrete

use regarding the production phase for structural frames based on very different materials and systems is small.

Figure 3.6 displays the distribution of energy use for the production of a typical cast in situ reinforced concrete structure, deducted from Björklund et. al (1996). A 250 mm concrete slab requires approximately 150 kWh/m^2 of fossil energy and 35 kWh/m^2 electricity. Some data on energy use for the production of concrete are given in Appendix F.

3.7.3 The usage phase

The energy demand for space heating and cooling of a building, during given outdoor climatic conditions and at a set interval of indoor temperature, depends on the conductivity (transmission), convection (air movement through leaks) and radiation through the climate shell, the ventilation rate and heat gains from people, equipment, lighting etc. The thermal inertia of a building can even out temperature fluctuations, through thermal storage and, thus, reduce the required heating or cooling energy. The main thermal fluctuation cycle in a building is the twenty-four hour period. The energy saving potential of concrete buildings is related to their thermal mass, and when concrete has the function of a vapour barrier in the climate shell, also to air tightness. Besides limiting the overall energy need for heating, these mechanisms also decrease the maximum effect required for the heating system. Concrete, however, has high thermal conductivity, hence a careful design to avoid heat bridges is essential. The impact of the thermal inertia depends on the effective heat capacity, i.e. the share of the total heat capacity that contributes to the heat exchange between component and indoor air during the fluctuation cycle. Furthermore, the indoor temperature must be allowed to fluctuate at least 2 to 3°C. Johannesson (1981) modelled the heat balance of rooms including the effective heat capacity using the analogy of electrical resistances and capacitances and finite difference equations for the calculations. For the 24-hour temperature cycle the active thickness of a concrete wall or slab in contact with the room is 90 mm from the exposed surface, at a thermal transmittance of concrete of 1,2 W/m^{2}K°. In a field study, Akander (2000) has compared measured effective heat capacity and analytical results based on the principles defined by Johannesson (1981) and found adequate agreement.

Convection is driven by differences in air pressure over the climate shell, caused by wind or thermology (stack effect) and depends on the air tightness. In buildings with mechanical exhaust ventilation, tightness has little influence on the energy requirement, as air leaks only substitute the fresh air taken in through valves. In the case of balanced or natural ventilation, air leaks can correspond to between 10 and 30% of the heating energy requirement. In either case, air leaks affect the thermal comfort and may lead to moisture related problems inside the climate shell.

According to 'Miljövårdsberedningen' (2000), the average annual energy needed in a new multi-family residential building under average Swedish climatic conditions for space heating and hot tap-water is 140 kWh/m² and the use of electricity is 35 kWh/m².

A typical energy balance for a residential multi-family building with balanced ventilation and heat exchange is shown in Figure 3.7. A certain amount of energy can be gained from sources other than the heating system, such as, solar energy depending on type, size and orientation of windows and energy from people and their activities. This is defined as 'free gains' in Figure 3.7.

Guidelines on energy balance calculations, including energy gains and thermal storage are given in the draft CEN Thermal performance standard for buildings, prEN ISO 13790, 'Thermal performance of buildings – Calculation of energy use for heating'. In this standard, the energy balance of a building is displayed schematically. See Figure 3.8. For a residential building, 5 W/m^2 gain from people and activities is used for calculations according to the mentioned draft CEN-ISO standard. Depending on the building structure and the technical systems, the energy gains from solar radiation and occupants can contribute to decreasing the amount of bought energy.

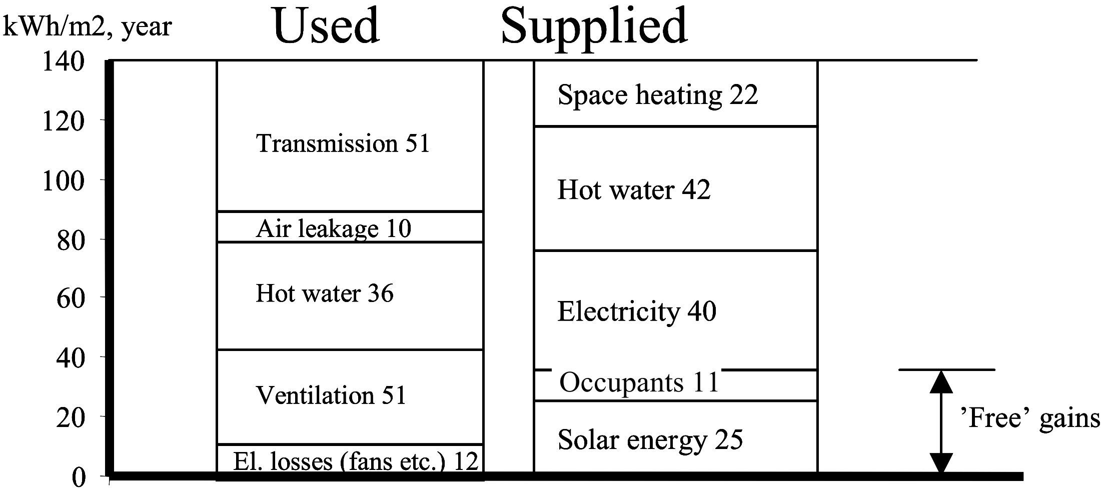


Figure 3.7 Energy balance of a low energy demonstration concrete multi-dwelling building with balanced ventilation built in Stockholm 1985 (BFR, 1986)

The Swedish building regulations (Boverket, 1998) state a maximum mean U-value for the climate shell for a residential building calculated by the formula; 0,18+0,95(Window area/Total enveloping area) [W/m^{2}K].

The requirement regarding max leakage is 0,8 litres/s m^2 through the building envelope at 50 Pa difference in air pressure. There is an opening in the regulations allowing for 30% higher mean U-value if it can be shown by calculation that the total annual energy use is not greater than for a theoretical reference building with the required mean U-value.

Environmental goals defined by the Swedish Ministry of Housing and Planning for new dwelling buildings state that the total annual energy use should be limited to 90 kWh/m² per year in 2010 and further to 60 kWh/m² per year in

2020. (Boverket, 1999). Accurate prediction tools are essential for the development of more energy efficient buildings. From the environmental perspective, the energy source is important and in particular the distinction between electricity and district heating or fossil fuels. Based on the efficiency of the production of electricity in coal or oil based power plants, 1 electrical energy unit is regarded as being equivalent to 2,5 units of, for example, district heating (Hejungs et. al. ,1992). From the environmental perspective, systems operating on electricity, such as heat pumps, must therefore be very efficient when there are non-electric alternatives available.

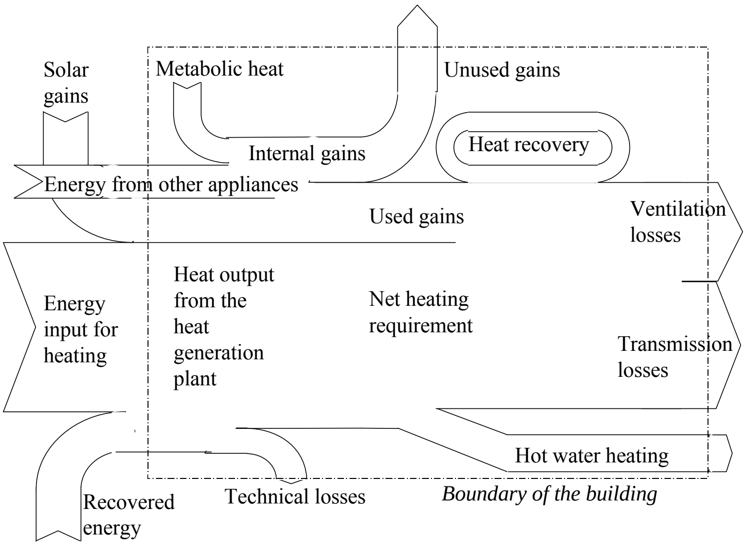


Figure 3.8 Energy balance for buildings according to CEN/ISO [Metabolic = from occupants]

3.8 Durability - Maintenance

To support decision-making in life cycle design, information of maintenance requirements for materials and systems is essential. This information can be systemised in a maintenance plan according to the example in Table 3.4. The maintenance plan should be considered as a basis for life cycle appraisal of costs and environmental impacts in the design phase, to aid choices between materials and components.

Concrete can be designed to last for a very long time without any surface protection or maintenance for the exposure conditions relevant to multi-dwelling buildings. The most aggressive environment is exterior surfaces exposed to de-icing salts such as stairs or balcony excess slabs, which are subject both to wetting and freezing. Also for those conditions, a maintenance free design life of more than 100 years can be obtained without any costly measures as regards concrete composition or reinforcement cover. Exterior painted concrete surfaces need maintenance according to Table 3.4.

*Table 3.4 Periodic maintenance costs. According to SABO (1999). * According to Persson (1999, p 102)*

Type of façade and maintenance activity	Maintenance Interval (years)	Cost (Euro/m2)	Annual cost (Euro/m2)
Rendering. Repair and colour.	30	23,3	0,20
Rendering. Exchange		62,2	0,53
Sheet steel. Exchange	42	64,4	0,27
Sheet steel. Repaint	14-25	11,7	0,14
Wood panel. Repaint	7-10	7,2	0,32
Wood panel. Exchange	35	38,3	0,33
Concrete. Repaint	14-20	6,7	0,11
Brick. Overhaul*	40*	15,0*	0,12*

3.9 Global environment and resource use

The important global environmental aspects related to buildings are the use of energy and materials. A third item related to materials is the use of dangerous substances. A Swedish national committee on the environmental impact of the building sector (BK, 2001) concludes, based on Life Cycle Assessment, that energy use for the operation phase is the most important aspect for houses. Compare Section 3.7. LCA methodology and its applicability in the building sector are discussed in Section 4.5.

Several LCA studies have been conducted on cement and concrete. Supported by the Nordic Industrial Fund, cement producers in Finland, Norway and Sweden initiated a comprehensive study that led to several reports, the first by Vold and Rönning (1995). Furthermore, LCA tools including databases were introduced for product development and the compilation of environmental product declarations for cement and concrete.

The environmental load of concrete increases with the cement content, compare Figure 3.6. If an optimal environmental performance is pursued, it is important, however, take in consideration that the basic functional quality aspects of concrete, such as strength and durability are also linked to the cement content. In respect of durability, service life design can be applied to establish optimal concrete composition with regard to the relevant exposure conditions.

To illustrate the importance of taking functional aspects into consideration by environmental design, Figure 3.7 shows the environmental impact on concrete elements according to LCA using the Effect Category weighting method (Hejungs R. et al, 1992). The wall element has a C30 concrete with plain reinforcement. The high strength product has a C85 concrete and pretensioned reinforcement. The beam is in between the other elements as regards material quality. Looking at the environmental impact, the low grade wall element is advantageous. However with a functional parameter taken into account, in this case the concrete compressive strength, the high strength product that requires a larger production effort is environmentally preferable.

The increase in cement content between the C30 and the C50 concrete strength classes in Figure 3.7 corresponds to 300 to 400 kg per m^3 concrete. The corresponding increase of energy use is approximately 20 kWh fossil energy and 4 kWh electricity per m^2 for a 250 mm concrete slab, which represents about 0,3% of the life cycle energy use. As regards the release of CO_2, the relation is about 1% calculated using the life cycle energy use of one building studied and the release of 0,710 kg CO_2 for the production of 1 kg of Swedish cement. Some environmental data on cement and concrete are given in Appendix F.

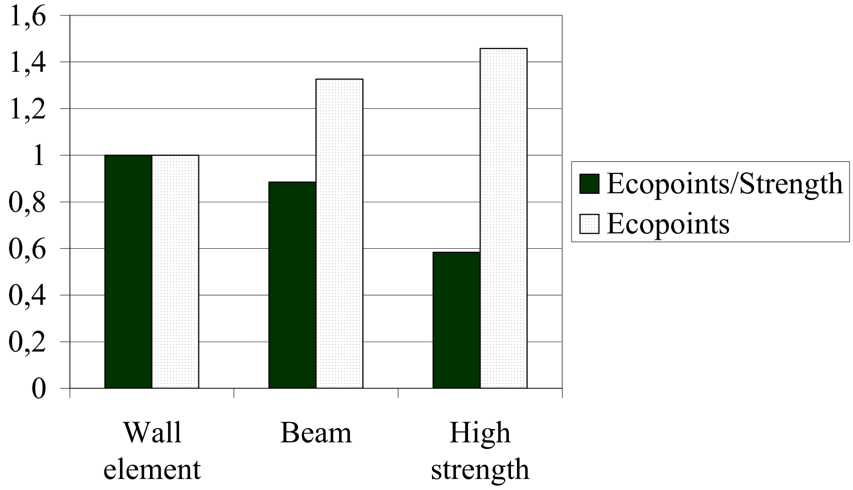


Figure 3.7 Environmental impacts of different concrete products according to the Effect Category weighting method (Hejungs R. et al, 1992) with and without taking functional performance expressed as compressive strength, into account. Wall: C30, Beam: C50 and High strength: C85 (Öberg, 2000)

Recycling of fresh waste concrete is done at the concrete plant where water and solid materials are separated for use in new concrete. The total amount of concrete waste in plant and on building site is approximately 2% according to Björklund et al (1996).

Concrete from demolished buildings or hardened production waste, is crushed and the reinforcement is separated. Crushed concrete can be used to substitute rock materials as aggregates for new concrete or by road construction.

3.10 Life cycle economy

Life cycle costs are discussed in detail in Chapter 5 where it is shown that about half of the life cycle cost, calculated as the present value, is related to the production phase of a dwelling building and the rest to the usage phase. The distribution of costs in multi-dwelling buildings of different ages and forms of tenure, according to SCB (1999), is presented in Figure 3.8. The largest variation between the different age groups lies in the capital costs. The cost of periodic maintenance and heating in new dwellings is about two thirds of that in old.

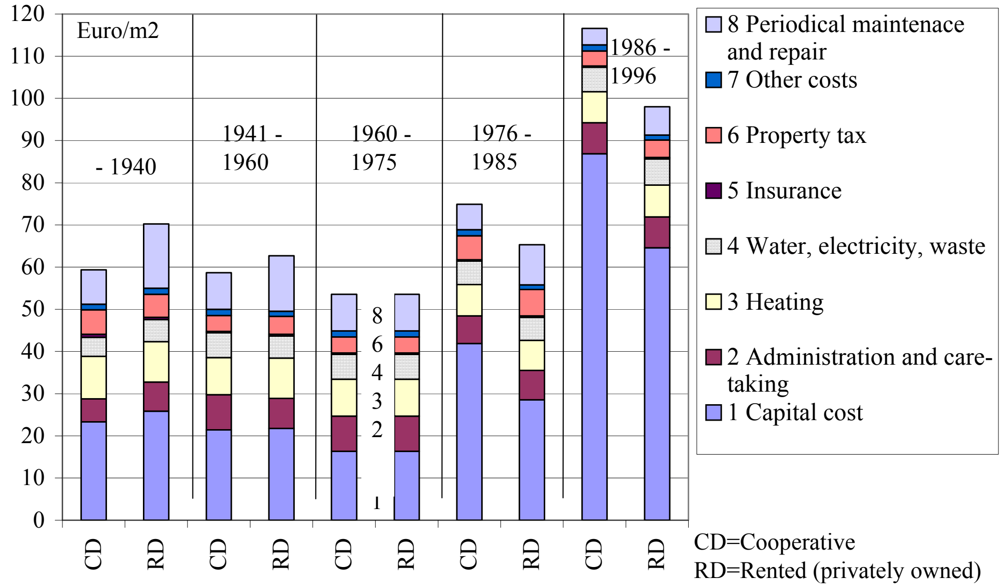


Figure 3.8 Distribution of costs in Swedish multi-dwelling buildings during 1998 according to age (SCB, 1999)

3.11 Lifetime functionality and usability

Functionality and usability indicate how well the building is suited for its intended purpose. Buildings have a long life span and the user requirements are, therefore, likely to change. This is obvious for office and industrial buildings, but is also relevant for residential buildings. Flexibility is a matter of several aspects such as:

- How interior partition walls can be rearranged in a flat
- How the general interior plan of the building can be changed
- How accessible technical support systems are for changes and maintenance
- How the size of the whole building can be altered vertically or horizontally
- How structures and systems do not intervene with adjacent systems

There are two possible strategies to obtain flexibility:

I To design for general flexibility. This implies a certain choice of structural and technical systems and usually a certain over capacity regarding different aspects, such as load bearing or ventilation.

II To design for a specific (predicted) future change. In this case, a more exact design can be made to match the extension or change.

The interior planning possibilities and in particular the flexibility for more substantial changes, are primarily dependent on the design of the structural frame, but also on the technical service systems. The most obvious way to facilitate flexibility is through long floor spans, which allow freedom as regards positioning of the interior walls and thus freedom in respect to size of flats and rooms. Some examples from the field study on life cycle cost in Chapter 5, can be presented. Figure 3.9, shows one entire flat that is free from load carrying walls, which means that the configuration of rooms is totally flexible. Another possibility is to increase height of the rooms in a dwelling building in order to allow for future changes, from residential to office use. Figure 9.3, below, indicates the usability potential, that can be obtained through life cycle planning regarding the access to technical service systems.

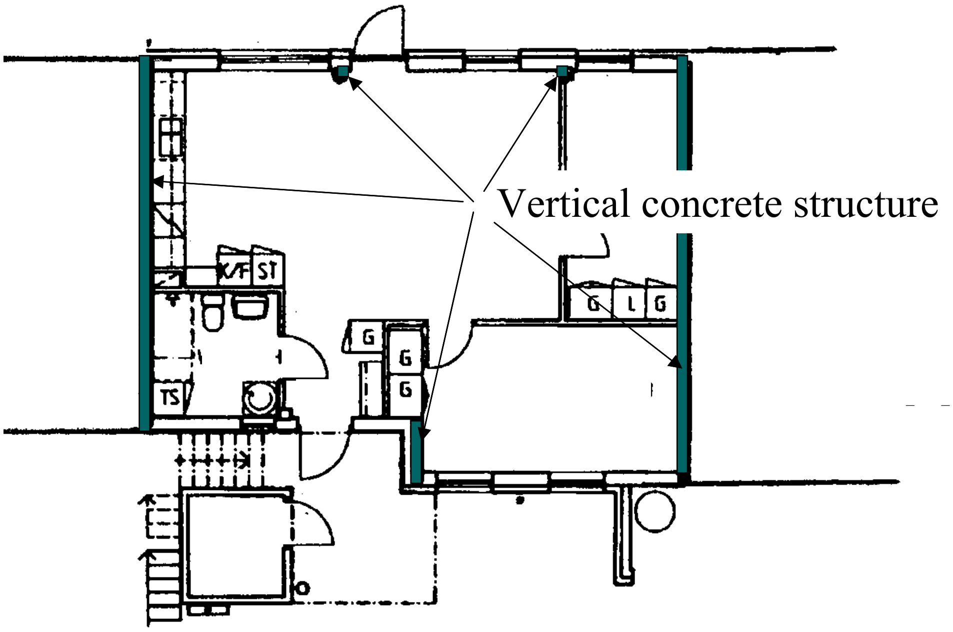


Figure 3.9. Plan of flat in the Erlandsdal project. No load carrying structures interfere with the layout of the flat

3.12 Social dimensions/Aesthetics

The exterior aesthetic appearance of a building is in the hands of the architect and the municipal planning authorities. The type of structural frame is seldom a restriction regarding the choice of façade material. A building with a lightweight frame can be made to look like a 'stone house' and vice versa. Concrete can be used as an aesthetically neutral material, but the expression of concrete is also a design feature. The technical possibilities are available at reasonable cost to provide most kinds of surface textures and colours, and the strength and plasticity of the material permits, in principle, unrestricted shapes. Hertzell (1996) has compiled a comprehensive handbook on architectural aspects on concrete surfaces providing examples and guidance on specification and production.

Concrete suffers from a negative image caused by the frequent use of precast façade elements in the vast social housing projects that were launched in Europe in the post war period to satisfy the enormous need for new dwellings, see Figure 3.10.

Figure 3.10 Early 1960s social housing with precast concrete

The negative image cannot however, be related to concrete as a material. The projects were the building sector's response to political planning decisions. As a contrast, modern precast is shown in Figure 3.11 to illustrate some aesthetical possibilities, such as a new type of sandwich façade element where the joints are hidden, and another where the joints are used as a design element.

Figure 3.11 Examples of façade designs of modern Swedish precast concrete dwelling buildings. Top left: Stockholm, 'The Arch of Bofill'. Concrete surface similar to sandstone achieved by washing the fresh coloured concrete. Top right and bottom left: Both Stockholm. Special 'joint free' sandwich element with lightweight aggregate in outer panel. Bottom right: Frösön, Jämtland. Painted elements with surface structure similar to rendering and joints used as design element.

Bottom right with permission of SCF Betongelement AB, Strömsund, Sweden, all other with permission of Skanska Prefab AB, Malmö, Sweden.

3.13 Robustness

Robustness represents the ability of materials, structures and systems to withstand wear, damage and regular as well as accidental or unintended loads and to limit vibrations and deformations with regard to the working load. A robust structure can easily be repaired after damage. Finally robustness can also imply that there is residual capacity in the structure to enable changes in terms of increased loads or introducing openings in an existing structure, etc. The resistance to regular wear and environmental exposure conditions is referred to as maintenance, which is discussed in section 3.8 above.

Robustness is also a feature relevant to the production phase. A robust technical solution, or production method, is less susceptible to conditions on site and it is tolerant with regard to quality of execution.

Typical problems for a multi-dwelling building related to robustness are for the production phase:

- susceptibility to the weather conditions on site
- technically difficult connections and details with regard to the insulation of the climate shell for moisture and heat
- tightness in the building

The user phase problems are, for example:

- mechanical damage caused by people
- water damage (leakage of water from internal or external sources)
- moisture, such as humid indoor air that meets cold surfaces and condensates
- excessive heat or cold, such as the ability to maintain acceptable indoor temperatures when the heating is cut off
- fire
- technical solutions that are risky from the building physical point of view

In multi-dwelling blocks, mechanical damage is primarily concentrated to common and accessible areas such as stairways, basements and street level façades. Water damage has certain similarities to fires, discussed in Section 3.3, in that the total extent of the damage depends on the ability of the structure to confine the spread of water. The severity of the damage is of course also connected to the material properties concerning water damages.

The robustness of buildings is in Sweden, to a certain extent, classified by so called insurance classes, ranging from class 1 for modern masonry or concrete frame buildings to class 4 for older wooden building frames. The relative insurance rates vary accordingly from 1 in class 1 to 2,8 in class 4 according to REPAB (2000)

Robustness is, in a broad sense, a typical feature for concrete, due to its strength, density and inorganic composition.

4. INTEGRATED LIFE CYCLE DESIGN - AN OVERVIEW

4.1 General

A building must satisfy a number of attributes as discussed in Chapter 3. Some of the attributes are variables that can be expressed in performance classes, for instance, sound insulation while others, such as safety, are unconditional requirements. Finally, economy and the environment are factors that should be minimised over the life cycle. These are in principle ‘expenses’ dependent on the designer’s skill in meeting the requirements of the building in an efficient way. Economy and environmental performance can thus be considered as consequential or resulting attributes.

The rationalisation of the production process and development of the intended product, in this case the building, need to be based on a holistic life-cycle perspective. This is the aim of *Integrated life cycle design, ILCD*, thus it is a key for whole life optimisation and sustainable development (Sarja, 2000). Integrated Life Cycle Design is a combination of two different principles:

- integration, which implies that different aspects should be considered with a holistic perspective. For instance the design of heating and ventilation systems should be done in collaboration with the structural design. Furthermore, integration indicates that the ranking of alternative design solutions is done in an aggregated way as explained Chapter 8.
- life cycle, meaning that the design should take, not only production costs, but also costs of maintenance and final disposal into consideration. See Figures 4.1 and 4.2 below.

	⇐ Life Cycle Design ⇒		
⇐ Integrated Design ⇒	Production	Use	Final disposal
Mechanical resistance and stability	▨	▨	▨
Safety in case of fire		▨	
Hygiene, health (indoor climate)	▨	▨	
Safety in use		▨	
Acoustics		▨	
Energy use	▨	▨	▨
Durability		▨	▨
Global environment and resource use	▨	▨	▨
Life cycle cost	▨	▨	▨
Life time usability/functionality		▨	▨
Aesthetics and social dimensions		▨	
Robustness	▨	▨	

Figure 4.1 Integrated life cycle design approach. Fundamental properties and their relevance to the different life cycle phases [grey boxes]

Normally all the attributes in Figure 4.1, and usually some additional ones, are addressed in the design of a building. Some attributes can be expressed using classes, such as sound insulation or fire safety/insurance classes with or without a certain minimum standard stipulated in regulations. Other aspects, for example mechanical resistance and stability are strictly defined by codes and thus acting as screening attributes, i. e. requirements that are unconditional. Some characteristics such as flexibility or aesthetics need to be described and evaluated in qualitative terms. External environmental (ecological) aspects and economy on the other hand, can be regarded as functions of the particular design chosen to fulfil the fixed/classified requirements. One main challenge in the optimisation process is to synthesize attributes that are qualitative as well as quantitative.

In order to visualize the interaction between attributes, an example of the potential consequences of one particular design decision is presented; Designing for improved acoustic performance from good [B] to the highest sound class [A], according to section 3.6.

Direct consequences:

- A column/slab [mushroom] or façade to façade spanning slab in order to achieve adequate airborne and impact sound reduction without flanking transmission, compare Section 3.6.
- A concrete façade along any side of the building facing traffic
- Floor coverings that reduce impact sound significantly
- Careful placement of installations, staircases and elevator shafts
- Low noise technical service systems

Indirect consequences:

Consequences as regards hygiene, health (indoor climate):

- Added thickness of concrete slabs must be taken into account with regard to the drying out of construction water.
- Concrete exterior walls improve air tightness and thus, the efficiency and stability of the ventilation system and reducing the risk of cold draughts.
- The amount of concrete surface exposed to indoor air and thus buffering temperature may change depending on the relation between the interior concrete walls that are removed and exterior walls that are added.
- Acoustically optimised floor coverings may reduce thermal buffering via upper surface of floors.

Consequences as regards energy use:

- Concrete exterior walls improve air tightness
- Thermal storage may be affected according to the discussions above on indoor climate.
- Changes in thickness of interior floors and walls affect the total building volume and thus increase the energy needed for heating

Consequences as regards indoor environment:

- Improved acoustics lead to an improved indoor environment
- Indoor temperature variations may increase if concrete surfaces are covered

Consequences as regards robustness:

- A concrete exterior wall is a robust technical solution from several aspects

Consequences as regards flexibility:

- Facade-to-facade spanning floors, or mushroom structures provides excellent possibilities for future changes
- The positioning of rooms must be done taking neighbouring activities inside and outside the building into account to avoid expensive and inefficient detail solutions. Bedrooms should not, for instance, be placed next to stairways and elevator shafts.

Consequences as regards life cycle costs:

- The choice of production method affects production time and costs
- Production costs increase
- Costs of future changes are decreased due to the flexibility of long span floors
- Robust exterior walls decrease maintenance costs

This example indicates that there are a large number of direct and indirect consequences following of a design alternative. ILCD supports understanding of these consequences and therefore a help to promote optimal solutions.

4.2 An overview of integrated life cycle design tools

ILCD represents a systematic way of defining and ranking requirements and optimising the design solution according to the priorities given in the particular project. Figure 4.2 illustrates the main areas of ILCD. As in traditional design, the process starts with the definition of requirements. To organise this, specific methods can be used as described in Section 4.3. The life cycle appraisal components of ILCD are inventory tools that elucidate the consequences over the entire life cycle or a selected time span for the 'resulting attributes', according to Section 4.1, i.e. life cycle costs and the environmental impact.

For the detailed design, traditional tools, such as building acoustics and structural design methods are used. Methods for energy balance calculations as a complement or alternative to Life Cycle Assessment, are discussed in Section 4.6.

A qualitative method for the assessment of the indoor climate, is presented in Section 4.7

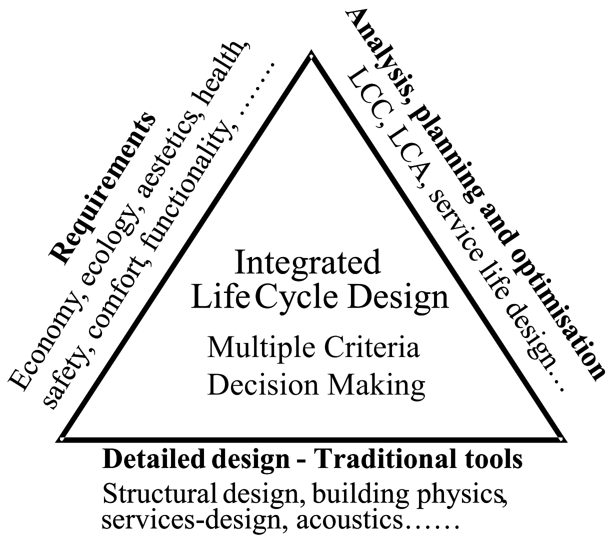


Figure 4.2 Principle for Integrated life cycle design of buildings

4.3 Aids to define requirements

The first step of the design process is the definition of the requirements on the building. Figure 4.1 shows some fundamental attributes to which a number of functional requirements are added. To organise the collection, interpretation and definition of the client’s needs as regards functionality, a product development method such as Quality Function Deployment, *QFD*, can be applied. QFD is used to support product optimisation in the design phase. QFD has been successfully applied in the manufacturing industry since the early 1980s. Akao (1992) defines QFD as a method for (i) developing a design quality aimed at satisfying the customer and (ii) translating the consumers’ demand into design targets and major quality assurance points, to be used throughout the production stage. QFD is thus a systematic way of tuning the product features to the client requirements and of documenting the decisions in the design process. It is organised as a set of matrices that addresses and defines information such as:

1 client requirements and needs
2 product characteristics that are required to match 1
3 the relation between 1 and 2
4 results from an analysis performed regarding alternative solutions
5 opposition between characteristics
6 target values for the required characteristics

QFD has been tried in the building industry on an experimental basis, but has not yet had any greater impact in practice. The International Energy Agency, IEA, has applied QFD to support the design of eco-efficient buildings according to the basic functional criteria; life cycle costs, resource use, architectural quality, indoor air quality, functionality and environmental loading. Nieminen and Houvila (2000) report some pilot cases where QFD was used with promising results both for the overall design of new buildings and for office refurbishments. Apleberger (1994) describes how QFD was tested to determine how the documentation should be organized in a building project. It stresses one particular advantage in that the requirements of all actors were systematically clarified. Apleberger proposes other construction related applications, such as the choice of structural frame, purchasing and material administration.

QFD may lead to extensive paperwork with several interacting matrices at various levels of detail. This may discourage, or prevent, its introduction in the building sector. Gargione (1999) mentions the following difficulties; substantial increase on time expended by the project management team, difficulties working with large QFD-matrices and processing the information put into it. There is, however, no foreseeable shortcut for rational and systematic design decisions and the challenge will be to adapt the QFD-concept to the needs of the building sector. The increased industrialization of the sector with more continuous production will probably work in favour of methods like QFD.

4.4 Life Cycle Costing

Life Cycle Costing, 'LCC', is used to identify and quantify consequences regarding costs related to a product during its entire life cycle. The term LCC was defined by Kirk and Dell'Isola (1995) as; *an economic assessment of investment alternatives that considers all significant costs of ownership discounted over the lifetime of a product.* Some authors (Gluch, 2000) refer to the United States Army in the early 1960s for the first application of LCC. It could, however, be argued that the general concept and calculation procedures can be traced back to the early 1930s when methods such as *Simple payback, Net present value* and *Internal rate of return* were introduced in the manufacturing industry to calculate the economic results of investments. In those applications, the profit is also taken into account (Dale, 1993). In practice, it is difficult to exclude profit, as there are normally such consequences related to any decision and from the owner's perspective, the life cycle cost and profit are seen in the same context. The initial and operating costs should be balanced by the rent and the secondhand value and, therefore, an expression such as life cycle economy would be more appropriate. The terminology Life Cycle Costing and Whole Life Costing are equivalent and the abbreviation LCC is used in this study.

During the 1950s, LCC was introduced in the building industry in the term 'cost-in-use' by Stone at the Building Research Establishment in the UK

(Ashworth, 1993). Stone used present values and annual costs to assess the cash flows throughout the lifetime of a building. In the UK, LCC replaced the term cost-in-use through the work of Flanagan and Norman (1983), who together with Meadows and Robinson also published the handbook *Life Cycle Costing: Theory and Practice*.

The British Standards Institution presented a standard, BS 3811, in 1974 describing the life-cycle phases from design to replacement that fits well with the organisation of LCC (and LCA). The method was further developed in the UK during the 1980s, promoted by The Royal Institution of Chartered Surveyors (RICS, 1980, 1986). There is also an available Norwegian Standard, NS 3454, *Life cycle costs for building and civil engineering work – Principles and classification*. An international standard for Whole Life Costing is being developed by ISO/TC 59/SC 14.

In Sweden, the LCC has been practised in the building sector since the 1970s (Arthursson and Sandesten 1981). This work applied primarily to investments regarding refurbishments and technical equipment. Sterner (2000) describes the experience of LCC in a case study comprising 54 Swedish users of LCC. The two top ranked constraints regarding use of the method were found to be experience and input data. Regarding reliability, the respondents found LCC estimates to be ‘mainly correct’ or ‘in some ways correct’ in 80% of the cases. The author concludes that LCC deserves to be used more frequently than is the case today.

Rutter and Wyatt (2000) argue that LCC is seen only as a tool for first decisions regarding design options and that it should be given a firmer link between the initial intentions and the subsequent implementation. To indicate this, the term LCC should be exchanged for ‘Whole Life Costing’. This discussion however seems a bit weak, as there is nothing that prevents the inclusion of the implementation phase, in LCC.

4.5 Life Cycle Assessment

Life Cycle Assessment, ‘LCA’, contains elements that are methodological parallels to LCC, but aimed at quantifying environmental aspects even though the term indicates a wider scope. The inventory part of LCA, ‘Life Cycle Inventory’, maps occurrences of environmental relevance over the life cycle of a product just as LCC maps the economical consequences. As opposed to LCC, the time aspect is not considered. A future occurrence has the same significance as the same occurrence today. A second difference to LCC is that instead of one currency unit, environmentally relevant occurrences consist of a large number of different items that in their turn often affect a number of different environmental impact categories. Thus burning fossil fuels emit, for example, CO and NO_x. NO_x causes both eutrophication and acidification. LCA methodology involves considering how these different aspects can be assessed jointly, which is a multiple criteria decision-making situation common to ILCD. Presenting the impact categories individually is one way of avoiding the problem and turning it over to those who will interpret the result.

Among the early applications of LCA were the Midwest Research Institute and the Coca Cola Company that in a study from 1969 compared environmental load and resource use for different types of beverage containers. In the 1970s, the focus was on production and the use of energy as a result of the oil crisis.

The next phase of the development of LCA occurred during the 1980s when it was acknowledged that the physical areas for the deposition of waste material were restricted and the interest in recycling and reuse increased. In the early 1990s, LCA gradually became more widespread and the method became standardised in the ISO 14040 series. SETAC, The Society of Environmental Toxicology and Chemistry, has co-ordinated this work and developed a ‘Code of Practice’ (Consoli et al, 1993).

The weighting methods developed for LCA, such as the Environmental Theme Method (Hejungs et al., 1992), or the EPS Environmental Accounting Method (Steen and Ryding, 1992), challenge the same problem as ILCD of making attributes comparable even though they cannot be measured with the same unit. The EPS method transforms aspects, such as resource use, emissions to water and emissions to air, to a common currency called a Environmental Load Unit, ‘ELU’. The ELU-value is based on relative willingness of society to pay to avoid a selected environmental protection domain, such as ozone depletion or eutrophication. The environmental impact of a product can thus be expressed in the number of ELUs, which can be used to rank alternatives, for instance by product development.

A large number of LCA studies regarding building products and systems and also entire buildings have been undertaken. There are many critical aspects to consider as regards, for instance, cut-off criteria, allocation, data quality, functionality and weighting methods. These issues can usually be treated appropriately when working with the application of LCA internally in an organisation for product or process improvement and the method is a good tool for this purpose. When comparing products of different character by LCA, for example, steel, concrete and timber, any conclusion must be very carefully judged and the requirements on transparency are very high. These problems are apparent in a report by Andersson (1998), which examines four different LCA studies, initiated by organisations for competing materials producing waste water pipes. The results are diverging and the lesson is to be careful when ranking the environmental impact of significantly different products.

The linking instrument between LCA and life cycle design is primarily the *Environmental Product Declarations, EPD.* Type III EPDs, (third party assessed declarations according to ISO 14025) are based on the inventory part of an LCA. Type II declarations (self-declarations according to ISO 14021) are also often based on a Life Cycle Inventory. A complete and up-to-date set of EPDs, preferably of type III to ensure reliability, for building products and systems is a key-enabler for environmental design. Also generally acknowledged principles for comparison of different environmental impacts, as discussed above, are needed. These conditions cannot be met in the near future.

Energy use during the operation phase may be considered as a proxy for the quantification of the environmental load of a building. Saari (2001) uses this simplification when assessing buildings, even though it is acknowledged that energy use does not cover the entire environmental field. Recent investigations based on LCA confirm that, so far, energy use during the usage phase is the most critical environmental aspect regarding Swedish houses (BK, 2001). A second reason for this simplification is that complete, robust and reliable EPDs for building products are only available for a limited number of products and materials, which makes any detailed LCA for a complete building unreliable. A quantitative EPD for cement is available from Cementa AB (2001).

4.6 Energy Balance Calculations

In a review by Bergsten (2001) on commercially available energy balance programs in Sweden in 2001, a total of 12 programs were accounted for, ranging from simple shareware tools, providing crude estimates for single-family house applications, to customized versions of sophisticated university programs. Energy balance calculation programs can be grouped into dynamic and steady state. Steady state programs work in principle like hand calculations and their main advantage is that the computation effort is very small as they exclude complicated algorithms and the time resolution is at least a whole 24-hour period. The accuracy of a steady state program depends on the similarity between the specific conditions and those for which the calculation has been adapted. Such programs are, therefore, suitable for simple and standardised buildings, such as prefabricated single-family homes, where calibrations could be made based on the actual performance. The combined effect of, for instance, surplus energy, air leakage and thermal storage, can thus be approximated but not calculated with a steady state program. The most used program in Sweden today, ENORM (1996), is a steady state program that was developed at a time when the capacity of common PC computers restricted the possibility of using dynamic programs. According to an analysis using this particular program on four multi family dwelling buildings by Adalberth (2000, paper 3, p 18), the actual energy use was underestimated by in average 27%, and in a validation on 16 multi family dwelling buildings by Sandberg (1998), by as much as 50%. Besides the limitations with regard to the calculation method in steady state programs, the large discrepancy can also be attributed to incorrect input data with regard to user behaviour and technical performance. For instance, there are approximated values for gain of solar energy and internal surplus heat based on experience of houses built during the 60s and 70s, that are not valid for the buildings currently produced. For general applications, such as multi-family dwelling buildings, dynamic programs are advisable. There are currently several user-friendly dynamic programs available according to Bergsten (2001). The European and ISO standard 'Thermal Performance of Buildings – Calculation of Energy Use for Heating', prEN ISO 13790, employs the steady-state approach but the effect of thermal storage is quantified with a so called utilisation factor, which is a function of the heat loss, heat gains and the time constant of the building studied. The time constant is defined as the total effective heat capacity divided by the total heat loss by transmission, convection and ventilation. Akander (2000) calculates the difference with regard to potential energy requirements in multi-family dwelling buildings with different thermal inertia with a dynamic energy balance calculation program and also with the above-mentioned standard and concludes that the calculated energy for heating the heavy building is 86-94% of the light building depending on the specific conditions.

The software VIP+ (1994) is a dynamic program that can assess the impact of thermal inertia and air leaks. The program manages energy supply from space heating, solar radiation, internal gains (people, appliances) heat recovery from ventilation and energy release by transmission, ventilation, air leaks, hot water production and cooling. There are two specially designed calculation modules, one to estimate airflows through the ventilation system and air leaks according to Nylund (1980) and one for heat capacity the according to Johannesson (1981).

4.7 Indoor climate

The indoor climate is a fundamental property of a building. To design for a comfortable and healthy indoor climate is a multi disciplinary task that needs consideration both as regards the building, its service systems and their interaction. One way of increasing the knowledge of indoor climate performance in relation to a particular building and service systems design, is to examine the quality in newly built houses that have been used for a few years. In Sweden, standard questionnaires on perceived indoor climate have been developed and used extensively since the early 1990s. 'SABO-enkäten' (Engvall and Norrby, 1992) is a questionnaire aimed at general evaluation of indoor climate. The result of the questionnaire is presented in the form of profiles of complaints covering; indoor temperature, ventilation, acoustics, light and health. The result is compared with a reference, based on a survey of over 10000 households in Stockholm, distributed by age of building, type of ventilation system etc. The second questionnaire was developed by the institute for working health in Örebro and focuses on explaining apparent sick building symptoms.

Design instruments available for indoor climate are principally the traditional building physics tools. Dynamic energy balance programmes can be used to predict indoor temperatures at the same time as the energy use is calculated.

4.8 Tools for Multiple Criteria Decision-Making

To support the optimisation process special methods can be applied, such as Multiple Attribute Decision-Making, *MADA*, originating from the manufacturing industry. An Analytical Hierarchy Process that enables the calculation of one single measure of desirability for alternatives with several attributes measured quantitatively and qualitatively supports MADA (ASTM, 1998). Typically, the MADA problem deals with a finite set of alternatives regarding attributes that are measured with different units, where no single alternative dominates. It is, thus, not a method for optimisation among an infinite number of solutions to a problem.

The method starts from a hierarchy expressed as a tree structure. This structure is transformed into a decision matrix, where the attributes are defined in one dimension, and the performance of the studied alternatives in a second dimension. The next step is to perform pairwise comparisons between the alternatives with regard to each attribute. This is done with a matrix of pairwise comparisons answering the question of how much more desirable one alternative is compared to the other. The same type of pairwise comparison is also performed between attributes where the question is how much more important one attribute is compared to the other. Verbal expressions are converted to numerical counterparts. Equal importance of attributes or equal desirability of alternatives are for example assigned 1, while extreme importance of one attribute compared to another, or extreme desirability of one alternative compared to another, are assigned 9. Final desirability scores can be calculated using linear algebra calculations of principal eigenvalues for the matrices. This type of calculation requires software that can solve principal eigenvectors of matrices. Sarja (2002 p 54) states that a complete and detailed MADA analysis can be done for large and important projects, or the development of entire building concepts, while in the design of ordinary buildings simplified ways of use are more appropriate.

4.9 Examples of integrated life cycle design and comparable approaches

One of the key problems addressed by ILCD is to compare features that are of a fundamentally different nature. Several procedures have been proposed, often has triggered by the need to introduce environmental aspects into the decision-making process. One approach is to attach socio-economic prices to the environmental impact and use monetary units in the comparison.

The Swedish National Roads Administration (SNRA, 1999) has defined socio-economic costs expressed in money/kg substance emitted to air for selected polluting gases. Compare Table 4.1

Table 4.1. Socio-economic costs for emissions to air according to the Swedish National Road Administration (SNRA, 1999)

Socio-economic	CO_2	NO_x	SO_2	VOC
cost. Euro/kg	0,00135	6,7	2,2	3,3

Thus, if the emissions related to a certain event are quantified, an environmental cost for this event can be calculated. Likewise socio-economic costs for travel times and accidents are defined. The planning of roads and bridges can thus be based on the integrated cost of pollution, investment, maintenance, accidents and travel time. This principle can also be applied on buildings. One problem with this procedure is that a future event has a lower economic value than the same event today while socio-economic values normally are the same irrespective of time.

When BKD (2000) evaluated the submitted proposals for a contest regarding affordable residential buildings, the following weighting scheme was defined: 40% for economy in terms of rent, 20% for indoor climate, 20% for resource use and global environment and 20% for functional quality for the user. For each attribute, detailed criteria were defined in the tender documents. This is a simplified ILCD approach.

NCC AB has developed a so-called EKO concept in Finland. (Perspektiv, 2001) The EKO concept is a design tool predicting economic as well as environmental life cycle consequences of a particular building design.

In Sweden a method, ‘ECOEFFECT’, to calculate and assess global environmental aspects, outdoor and indoor environment, as well life cycle costs, has been put forward (Glaumann). ECOEFFECT compares 14 items grouped in five main impact areas with a reference, which could be an alternative design, or some general reference building. There is no key between the different impact areas. Thus, the method does not attempt to rank for instance costs towards environment. This is a sound and reasonable limitation common to many LCA methods as discussed above. At some point in a decision-making process, however, the different aspects may be in conflict and guidance will then be needed. The ECOEFFECT method only considers costs defined as related to the environment. This is a fair approach in a limited decision situation, such as if a particular energy saving measure is considered. Looking at an entire building in the design phase, it is difficult to define what is an environmentally related cost.

Jönsson (1998) discusses how to include indoor climate aspects in LCA. She concludes that from a methodological point of view it is possible, but that there are no scientifically verified ways of weighing the effects of indoor climate against external environmental aspects. Jönsson also points out that the LCA studies that so far have been undertaken in the building sector, are material or product related, while indoor climate is a function of a complete room or building. Thus, it is not possible to link indoor air quality with a particular type of flooring material, as a number of other parameters such as ventilation, installation procedures, adjoining materials and cleaning, must also be taken into account.

Saari (2001) presents a method to evaluate environmental burdens and life cycle cost, were energy use is employed as an environmental indicator. Target values for energy use are defined in the design phase based on the type of activity in rooms, areas and in-use times, according to the space programme. This target consumption is compared with estimated energy use for the designs considered.

5. LIFE CYCLE COSTS IN SWEDISH MULTI-DWELLING BUILDINGS

5.1 Life cycle costs in Swedish multi-dwelling buildings - an overview

In order to analyse life cycle costs of concrete multi-dwelling buildings and to establish methods for life cycle cost prediction, data on building and operating costs were gathered and analysed. Statistical data on costs was collected from several sources, as presented below and a case study comprising four modern concrete multi-dwelling buildings was undertaken.

A spreadsheet tool for present value calculations, adapted for multi-dwelling buildings was developed and tested on the buildings in the case study. The result spreadsheet of this tool is displayed in Appendix B. Parameter studies were conducted to evaluate the potential effect on costs of different designs.

5.2 Case study on costs in modern Swedish multi-dwelling buildings

Building and operating costs of four modern Swedish concrete multi-dwelling buildings were collected and analysed. The buildings were chosen to represent a broad spectrum as regards production method, tenure and geographical location.

Table 5.1. Basic data for the projects in the field study

	Terränglöparen	Joggaren	Erlandsdal	Aspnäs
Location	Stockholm	Stockholm	Svedala, Skåne	Frösön, Jämtland
Completed in	1994	1994	1998	1995
Owner/ Tenure	Co-operative	Co-operative	Semi-public/rental	Private/rental
Structural frame	In situ concrete on precast floor slabs	Precast concrete	In situ concrete on precast floor slabs	Precast concrete
Façade	Curtain wall. Brick	Concrete. Sandwich element	Curtain wall. Brick	Concrete Sandwich element
Roof	Concrete tiles	Concrete tiles	Concrete tiles	Sheet steel
Ventilation	Mechanical exhaust	Mechanical exhaust	Mechanical exhaust	Mech. exhaust with heat exchanger
Heating	Hot water radiators	Hot water radiators	Hot water radiators	Hot water radiators
No of flats/floors	58/5	60/5	64/2	52/4 + basement
Usable/Gross floor area	0,74	0,74	0,85	0,65

Sidan ersätts med den med bilderna
På som tar mycket datautrymme

Figure 5.1. Buildings in case study. From top left to bottom right: Terränglöparen, Joggaren, Erlandsdal and Aspnäs.

Terränglöparen', and 'Joggaren', Lidingö

The buildings belong to two groups of five 4-5-storey apartment buildings built in the vicinity of Stockholm. The projects were completed in 1994 and formed the basis for a case study with the aim of comparing different aspects of cast-in-situ technology with prefabrication (Paus, 1996). The study was initiated by the construction company JM Bygg AB. Both Terränglöparen and Joggaren are own development projects designed by the architect company FFNS AB in Stockholm for JM Bygg AB. The ownership was transferred to housing co-operatives some years after completion.

Erlandsdal 1B. Svedala

Erlandsdal 1B was built in 1998 by PEAB AB for the semi-public company Bostads AB Svedalahem on a modified design and build contract and it was designed by SYDARK architects. The project received a lot of attention for its ambitious goals to reduce production costs and rent levels, primarily by re-engineering the building process, with an approach designated 'Svedalamodellen'. The total production cost was 900 Euro/m2, VAT included, which was 33% lower than the average production cost according to SCB (1999). Apart from an improved building process, this can also be attributed to rational and simple design solutions and low land cost.

Identical kitchens and bathrooms were chosen for all flats ranging from 1,5 to 4 rooms. It should be pointed out that the cheapest alternatives with regard to production costs were disqualified in favour of solutions with presumed lower maintenance costs and better functional performance. For example, relatively long free span floors allow full flexibility in each flat, see Figure 3.9 above, and the façade cladding selected was brick instead of cheaper wood panelling.

Aspnäs 7. Frösön

'Aspnäs 7' is a privately owned one-block 3-4-storey apartment building on Frösön in Jämtland, comprising 52 apartments and a substantial basement floor. Skanska AB constructed the building in 1995 on a design and build contract, in co-operation with the precast concrete company SCF Betongelement AB, for a private investor. The architectural work was done by FFNS AB in Östersund based on a dwelling building concept developed by the precast company.

5.3 Analysis of costs. Case study and statistics

5.3.1 Initial costs

Initial costs, which are referred to as capital cost in Figure 3.8, can be grouped into development costs and construction costs. The development costs consist of costs for land acquisition, municipal fees and design. According to the statistics (SCB, 2000), the total development cost for the average multi-family dwelling building in 1998 was 190 Euro/m². The location of the project is important for development costs and in particular the cost for acquisition of land. In the Stockholm area, development costs were on average 240 Euro/m², while in smaller communities

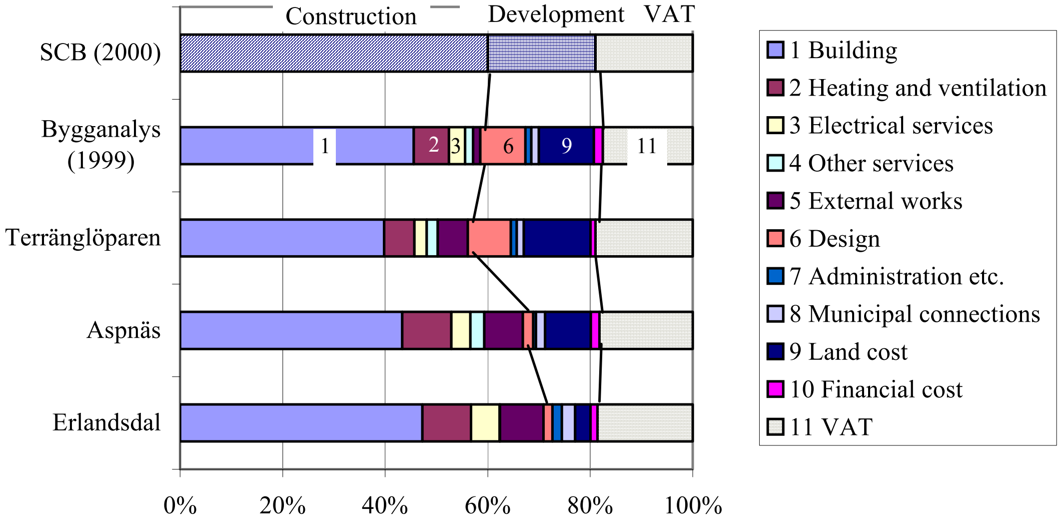


Figure 5.2 Distribution of initial costs for projects in the field study, according to the statistics (SCB, 2000) and the cost guide (Bygganalys, 1999)

the average was 170. This is one explanation for the differences in distribution between development costs and construction costs in Figure 5.2. Figure 5.2 shows the distribution of initial costs in the projects in the case study, according to the statistics (SCB, 2000) and according to a cost guide 'synthetic' (Bygganalys, 1999). The costs accounted for in Terränglöparen and Joggaren are average costs representing three similar blocks. In Table 5.2 the production costs for Erlandsdal and Aspnäs are presented in detail. Costs displayed refer to date of construction.

Table 5.2 Production costs according to case study for Erlandsdal and Aspnäs

	Erlandsdal		Aspnäs	
Cost category	Euro/m²	Share	Euro/m²	Share
Development costs				
Site cost	29	0,25	92	0,60
Design cost	18	0,15	11	0,07
Municipal connections	25	0,21	18	0,12
Other development costs	31	0,27	23	0,15
VAT	13	0,12	9	0,06
Subtotal	**116**		**154**	
Construction costs				
Foundation	25	0,03	39	0,05
Concrete frame	71	0,08	186	0,21
Structure completion	198	0,22	112	0,13
Internal finishes etc.	139	0,16	86	0,10
Service systems	139	0,16	154	0,18
External works	69	0,08	72	0,08
Preliminaries	70	0,08	50	0,06
VAT	177	0,20	175	0,20
Subtotal	**888**		**874**	
Total	**1004**		**1028**	

It can be noted that the land cost of the Erlandsdal project is very low, and that the concrete frame in Aspnäs, which is a precast structure with concrete façades, constitutes a larger part of the building than the concrete frame in Erlandsdal. It should also be stressed that the buildings are different in many respects, compare Table 5.1, and that no conclusions with regard to cost-effectiveness between the projects should by no means be drawn. The purpose of the study is to verify orders of magnitude with regard to the distribution of production costs for concrete multi-dwelling buildings.

5.3.2 Operation costs

Municipal services

The main services are supply of energy and water, and handling of waste and sewage. As regards water and waste, and also shared electricity in the building (for lifts, general lighting etc.) the cost is only influenced by the design solutions available to a limited extent, using traditional technology. The cost is thus mainly determined by the relevant local rates.

The rates for municipal services vary substantially. Smaller communities tend to have higher costs, but prices differ even between the same sizes. According to EKAN (2000) the cost for the services mentioned for a type building comprising 1000 m2 and 15 flats is in average 20% higher in the smallest communities with fewer than 7500 inhabitants compared to the largest with more than 60000 inhabitants. Looking at individual communities with more than 35000 inhabitants the cost ranges from 17 Euro/m^2 in Östersund to 27 Euro/m^2 in Karlskrona. In communities with fewer than 15000 inhabitants the range is from 17 to 30 Euro/m^2. Table 5.3 shows the average municipal costs for 1998 and 1999 for the buildings in the case study, and the 1000 m^2 type building according to EKAN (2000). Note that the total area of the type building is only about one quarter of the areas of the project in the case study, which explains the cost difference to some extent. The low electricity cost in Erlandsdal is due to the absence of elevators and an interior stairway. Furthermore, each flat in Erlandsdal is equipped with a washing machine instead of a communal laundry room, which is why electricity for this activity is accounted for in the individual flats.

Table 5.3 Municipal costs for case study and type building (Euro/m^2, year)

	Erlandsdal	Aspnäs	Terränglöparen	Joggaren	EKAN (2000)
Water/sewage	3,2	1,8	1,9	2,3	4,4
Space heating	6,0	7,1	7,6	8,6	11,3
Electricity for common use	0,1	2,4	2,6	2,2	1,6
Waste	1,4	0,4	0,6	1,1	1,8

The municipal costs are closely related to environmental aspects and presumably the price increase of these items will be higher than the general price increase. Deposition of combustible waste will for instance not be permitted in Sweden after 2002, and deposition of organic waste will not be permitted after 2005.

Administration and Care-taking

Administration costs are dependent on the form of tenure, social stability of the residents, size of the housing enterprise, and the geographical distribution of the buildings, size of the flats and other parameters that are not primarily related to design choices. Care-taking costs on the other hand, will also reflect robustness and aspects including cleaning and maintenance faciclity, which directly correspond to characteristics of the materials and components chosen. In the case study administration costs vary between 1 and 3 Euro/m², year and the care-taking costs ranges between 3 and 4 Euro/m², year. According to REPAB (2000), 3 Euro/m²,year is the typical administration cost for a building with normal administrative efficiency and 4 Euro/m²,year is the normal care-taking cost.

Insurance

The insurance cost is dependent on the insurance class of the building. For residential buildings there are four classes in Sweden referring to type of material in separating structures and the age of the building. The class with the lowest insurance cost has concrete or masonry in the exterior walls and floors separating flats, while in the class with the highest cost these are of timber. Here the cost relation is 1:2,80. For a normal multi-dwelling building, the insurance cost varies between 0,3 and 0,8 Euro/m², year (REPAB, 2000). The buildings in the case study have an annual insurance cost of 0,2-0,3 Euro/m². Besides the insurance class, the cost is also dependent on the excess chosen.

Periodic maintenance

The effort needed for periodic maintenance is dependent on the long-term behaviour of the building materials and components in relation to the particular exposure conditions. Therefore, they are directly dependent on the design of the building. Information on the long-term behaviour of materials and components can be obtained from producers of components, systems and materials and from cost surveying companies. Some large-scale owners, or organisations of owners, also collect data. The specific data needed is longevity, maintenance interval, maintenance procedure and cost per maintenance occasion. (Arthursson and Sandesten, 1981, REPAB, 2000, SABO, 1999). In Table 3.3 above, a part of the comprehensive list on maintenance data in SABO (1999) is presented.

The owner of the building must also optimise the maintenance activities over time in such a way that the deterioration of materials is kept under control. According to REPAB (2000), the cost for planned periodic maintenance varies between 1 and 14 with a median of 6 Euro/m², year. REPAB also defines an average repair cost of 3 Euro/m², year that is also a form of maintenance cost. The buildings in the case study are so young that relevant costs for periodic maintenance cannot be obtained.

5.4 Life cycle cost prediction

5.4.1 Life cycle cost calculations – formulas and assumptions

The discount rate is of significant importance for an LCC-calculation. The discount rate can be determined using assumptions with regard to the real interest rate, and the change of the price of the particular item, in relation to the consumer price index. The real interest rate is defined as the nominal interest rate minus inflation according to the consumer price index (CPI). The following example shows how the discount rate for a specific future cost can be used determined:

Real interest rate: 3%
Development of costs for the item in relation to the CPI: +0,5%
Discount rate for item: 3%-0,5%=2,5%

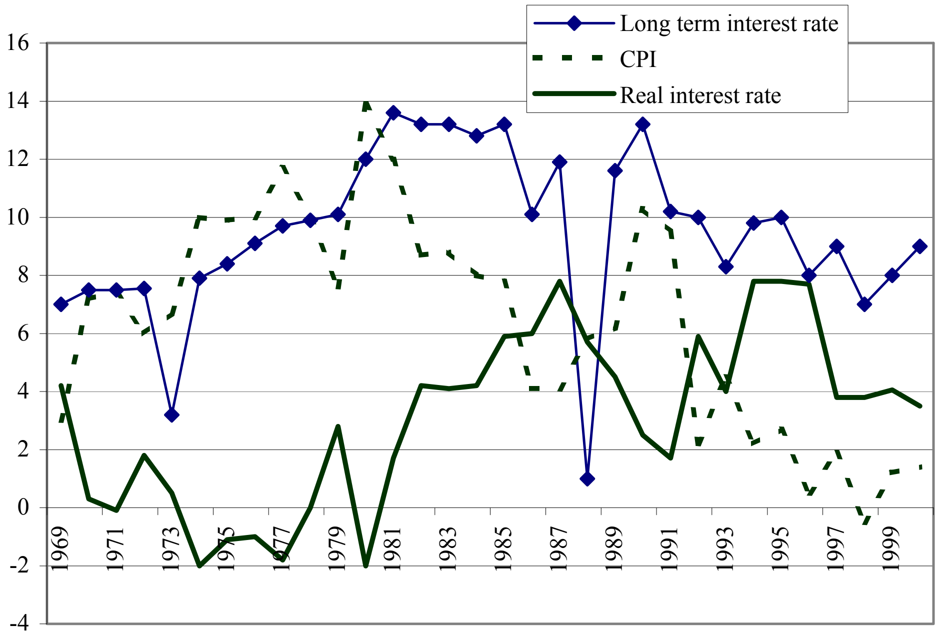


Figure 5.3 Long-term interest rates - bonds, consumer price index and real interest rate according to the National Bank of Sweden

The price change in comparison with the CPI is normally small. One exception with regard to the items, relevant to life cycle costs for buildings, is energy and other environmentally related prices, which can change radically. Sensitivity analyses are thus motivated. The real interest rate varies over time and this must be considered for the short-term perspective. Looking at a longer time span, for instance 50 to 100 years, which are relevant to the design of a multi-dwelling building, a historical average real interest rate can be applied. According to Figure 5.3, a real interest rate in the range of 3-4% can be derived for the past 33 years. It is reasonable to assume this rate for the long-term perspective.

Present value calculations

A spreadsheet tool for multi-family dwelling buildings has been developed that incorporates the calculation of the present value and annual provision of periodic maintenance. Data regarding maintenance intervals and cost per occasion was collected from SABO (1999).

The present value of a future event is calculated with the standard formula:

$PV= P_n\, p/(1-(1+p)^{n})$ where (5.1)

P_n =cost for event at price level when it occurs
n=number of years until event occurs. Here: 60 years
p=discount rate. Here: 2,5% for all items
Here: p=real interest rate minus annual increase of price above CPI

To estimate the annualised cost for periodic maintenance over the building life cycle, provision for future maintenance can be estimated. In this study, the annual provision of future maintenance was calculated as:

$a =S_n*p/((1+p)^n-1)$ where (5.2)

a=annual cost for provision of future maintenance and repair
S_n =cost for repair or maintenance at the point when it will occur
p=discount rate
n= interval for maintenance or repair activity

5.4.2 Life cycle cost calculations on the case study buildings

The relation between production and operation costs over the life cycle, for multi-family dwelling buildings, is roughly 45/55 (Johansson and Öberg, 2001). According to Griffin (1993) 50 to 80% of the total cost will occur during use.

Using the spreadsheet tool, that was developed, the life cycle cost was calculated, expressed as a present value, for the type buildings in the case study. In Figure 5.4 the distribution of life cycle cost expressed as present value for the four buildings in the case study is shown.

A large part of the total present value of costs is dependent on the design of the building, as indicated in Figure 5.4. This indicates that there is a potential for cost savings through careful design.

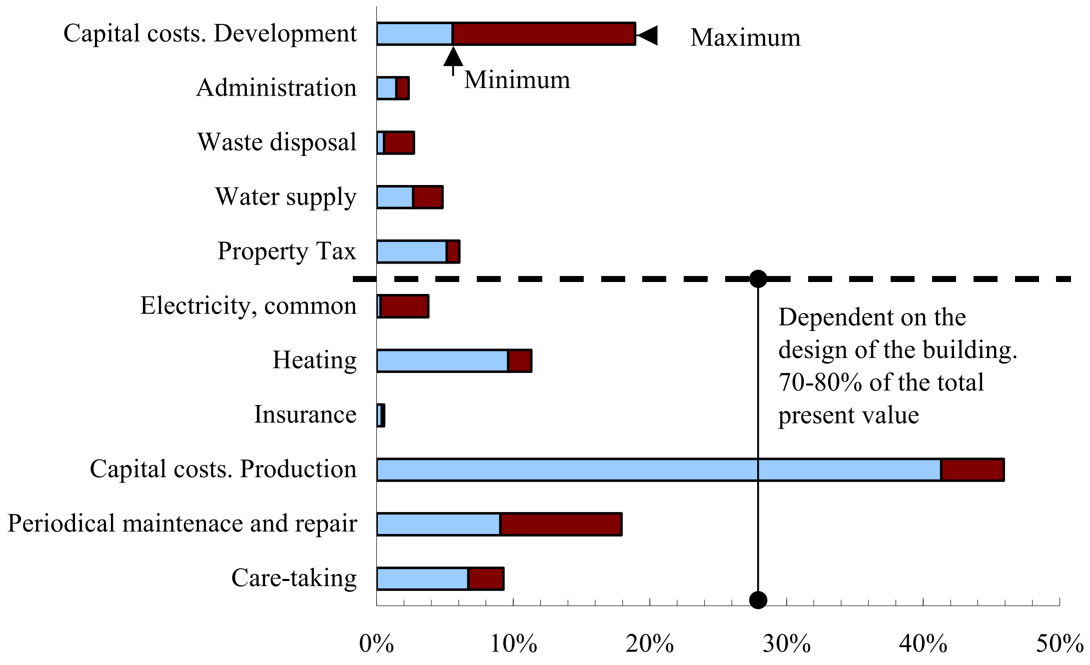


Figure 5.4 Present value (relative) of lifecycle costs for four different residential buildings according to Johansson and Öberg. (2001)

The most significant operating cost categories; energy and periodic maintenance, also have a substantial environmental impact for which life cycle optimisation is beneficial. It should be pointed out that during the last few decades roughly half of the total investment in the residential building market in the EU, with small regional and annual variations, refers to reconstruction (SCB 2000). This stresses the importance of the life cycle perspective. Both sufficiently accurate tools for the prediction of energy use in buildings and detailed information on the need for periodical maintenance for different materials and systems are available to assess LCC, depending on the design choices.

5.5 Parameter studies on life cycle costs

LCC can be applied in the design phase to assess total costs for alternative solutions. Whole buildings, or single systems or components, can be studied, which will be illustrated by two examples, referring to the case study project Erlandsdal. The first example refers to alternative designs for the whole building, discussed in the early design phase of the project, and described by Persson (2000) The second example deals with alternatives for a part of the building – the façade.

Example 1. LCC for an entire building

One alternative is the design built with a concrete frame and brick façade, which is compared to a timber frame with wood panel façade. Data regarding production costs for alternative designs were collected from Persson (2000, p 60). Operation costs used were the actual costs collected for the case study, referring to 1999. Periodic maintenance was calculated according to SABO (1999). Data on energy use were taken from the parameter study described in Chapter 6, with the actual costs 1999 as reference. Insurance costs according to REPAB (2000) were applied also with the actual costs year 1999 as reference. The residual value of the building was calculated as the present value of the initial cost at the end of the calculation horizon, which is 60 years. With the maintenance plan applied, compare Table 3.4, the condition of the building and thus the technical value is intended to be stable. Further data are presented in Appendix B. The results are presented in Table 5.4. The importance of the operation phase is obvious. The timber frame/wood façade has the lowest initial cost, but over the life cycle costs the alternatives are basically equal. Note that the periodic maintenance covers to the entire building, including interior surfaces, and that only a minor share refers to the building frame and the façade.

The conclusion in this particular case is that other criteria than direct life cycle costs can determine the choice between the two alternatives. One particular feature of the concrete alternative that may be difficult to assess, in monetary terms, is the long span floors, that allow full flexibility with regard to the location of the interior walls in each flat, compare Figure 3.9 above.

Table 5.4 Study on life cycle cost consequences on the whole building of different building frame and façade. Euro/m²

	Concrete frame/brick façade		Wood frame/wood façade	
Item	Annual cost	Present value	Annual cost	Present value
Initial cost	31,1	963	29,6	912
Administration	0,8	23	0,8	23
Waste	1,4	55	1,4	55
Water and sewage	3,2	101	3,2	101
House tax	5,2	160	5,2	160
Common electricity	0,1	6	0,1	6
Heating	6,0	238	6,1	240
Insurance	0,3	10	0,7	20
Care-taking	3,6	110	3,6	110
Other costs	0,8	23	0,8	23
Periodic maintenance	9,6	296*	10,4	324*
Value at end	-7,1	-219	-6,7	-207
Total	**55,1**	**1766**	**55,1**	**1768**

** 11 and 39 Euro/m² respectively refers to the façades and nothing to the interior frame*

Example 2. LCC for a component of the building

Here three alternative façade designs are compared. The direct and indirect life cycle costs that can be related to this particular component are included. The alternatives are complete insulated exterior curtain walls with equivalent thermal insulation. Apart from the brick and wood panel from the previous example, a concrete sandwich wall alternative is also studied. The calculated present values of costs are shown in Table 5.5 and in relative terms in Figure 5.5. Note that there are often secondary effects, such as heating and insurance costs in this case, that need to be taken into account.

Table 5.5. Present value of life cycle costs Euro/m2, façade area. 60 years

	Brick	Wood panel	Concrete
Initial costs[1]	121,2	75,4	107,1
Heating difference[2]	3,1	3,1	0,0
Insurance difference[3]	0,0	10,7	0,0
Periodic maintenance[4]	5,6	38,6	9,0
Residual value[5]	-27,6	-17,1	-24,3
Total	**102,3**	**110,7**	**91,8**

[1] *Costs for brick was the actual production cost. Wood panel was the unit price for this alternative calculated by the contractor. The concrete sandwich panel price was collected from Wikells (2001/02) correlated with the actual prices for the brick wall of Erlandsdal.*

[2] *Calculated difference in heating according to VIP+ (1994): 1,3%, due to thermal storage in the concrete exterior wall. Other parameters equivalent. Total heating cost 2000 divided by façade area used as reference cost for brick and wood panel.*

[3] *Actual insurance cost distributed by façade area. The higher insurance rates according to REPAB (2000) for a timber building are both related to interior and exterior structures. In this example half the difference in cost is allocated to the façade wall.*

[4] *According to SABO (1999)*

[5] *Present value of initial cost referred to the end of the calculation horizon.*

This example shows the importance of considering the operation phase and also that there are often indirect economic consequences attached to the alternative design, that may be difficult to spot and allocate. It is, therefore, safer to evaluate the entire building instead of single components and systems. For instance it should be noted that concrete sandwich walls are normally used as load carrying structures and that the costs in such cases must be assessed bearing the complete corresponding function of the other alternatives, in mind.

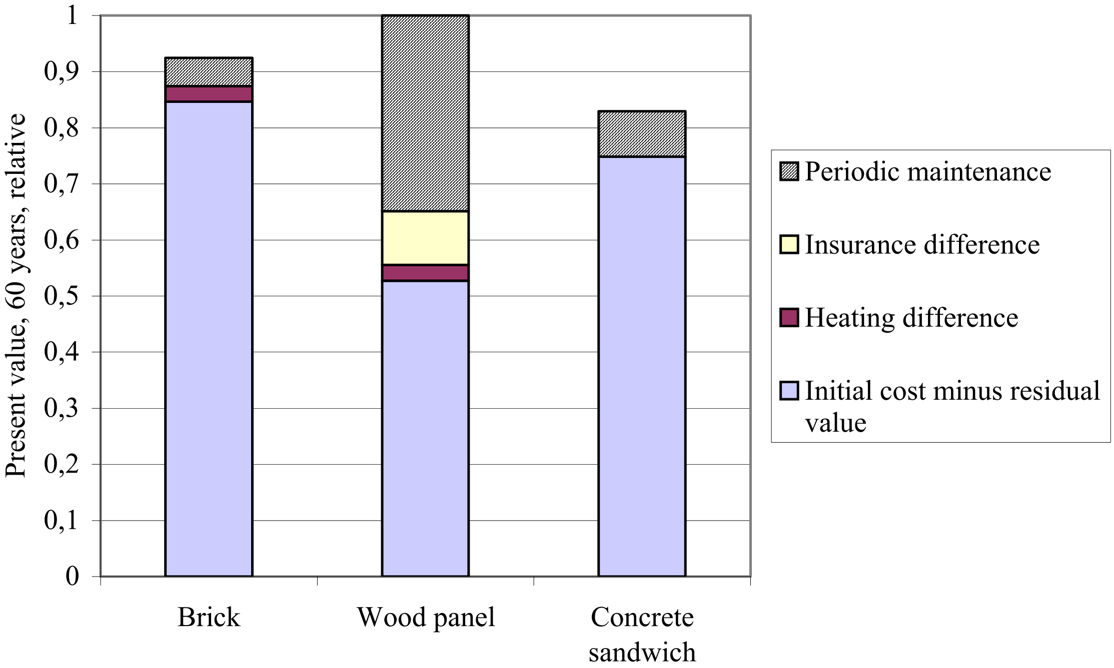


Figure 5.5 Life cycle cost comparisons of three alternative façade designs

5.6 Life cycle costs - conclusions

About half the life cycle cost refer to the operation phase. Periodic maintenance, heating and care-taking are the most important items with regard to operation cost, and they are all dependent on the design of the building. Data on periodic maintenance for different materials, systems and components are available. Heating costs can be estimated with energy balance programmes. Care-taking and other costs can be determined on the basis of statistics.

Traditional LCC calculations can be applied in the design phase to assess the economic consequences of the alternative designs considered. A simple tool for calculating life cycle costs expressed as present value, or annual costs, has been developed.

With regard to life cycle costs, the field study showed slightly higher production costs for the alternative with concrete frame and brick façade (4%) compared to the wooden frame with wood panel façade. However, looking at life cycle costs, this is balanced by lower costs for periodic maintenance, insurance and energy. In this comparison, differences as regards functional performance such as flexibility and acoustics, were not taken into account. Calculating LCC for alternatives regarding a single component or system, the differences between alternatives presents themselves more distinct. Particular care should, however, be taken not to leave out indirect cost consequences, that may follow a particular alternative.

6. VERIFICATION AND PREDICTION OF ENERGY USE IN MULTI-DWELLING BUILDINGS AND DISCUSSION ON ENVIRONMENTAL CONSEQUENCES.

6.1 General

The aim of this investigation is to verify a method for the prediction of energy use during the operational phase, that can appreciate the energy characteristics of a concrete building such as thermal capacity and air tightness. The potential with regard to energy savings can then be examined in a parameter study. One of the buildings from the case study presented in Section 5.2 was used as reference for the verification, as well as for the parameter study. The Erlandsdal building in Svedala was selected due to its simple geometry, which reduces sources of errors that do not relate to the issues studied. A computer program for energy balance calculations (VIP+ 1994), described in Section 4.6 was selected.

For the evaluation of environmental consequences, simplified LCA methodology was applied. The study was limited to energy use related environmental impact for reasons discussed in section 1.1 above. In order to obtain a direct comparison between economic and environmental aspects, a socio-economic model was applied, where important emissions to air have been assigned a price. Energy use according to measured or simulated use of energy for heating, hot tap water and electricity was mapped. The energy use for production was estimated using values from similar buildings according to Adalberth (2000, paper 3, pp 7-14). This relates to electricity and fossil fuels at the building site and used for the transportation and production of building materials. During the operational phase electricity and energy for heating are used, which in the Erlandsdal case, was natural gas.

Emission factors from the particular energy sources including extraction and use; natural gas and electricity, were collected from a database for the computer program 'Life Cycle Inventory Tool' (LCAiT, 1996), see Table 6.1. Only the emissions addressed by the socio-economic evaluation according to SNRA (1999), presented in Table 4.1, were mapped.

Table 6.1 Emissions from different energy sources

Emission factors for selected energy sources (g/MJ)	CO_2	NO_x	SO_2	VOC
Electricity. Swedish mix	12	0,02	0,01	0,003
Diesel	83	0,9	0,06	-
Natural Gas	62	0,06	-	0,002

These emissions are deemed to be representative with regard to the most severe global ecological damage, such as global warming, eutrophication, acidification and ozone depletion. Other substances also contribute to these harmful effects but in the case of energy production, these other emissions occur with good correlation to the selected substances. A spreadsheet tool was developed that calculates emissions, costs and socio-economic costs of the use of oil, electricity, natural gas and district heating, compare Appendix D.

6.2 Verification of energy balance calculations

Charged energy use for space heating and electricity for households and common areas during 2000 and 2001 was obtained from the owner Bostads AB Svedalahem. In order to refine the evaluation of the program, quantifications regarding hot tap water use, actual gains from people, and use of electricity, were applied instead of available default values in the computer programme. One block of flats comprising 8 flats was studied. The indoor temperature, 22ºC, and the number of tenants, 16, were determined by the questionnaire used for the survey on the indoor climate described in section 7.2. Climatic data for Lund, 2000 and 2001, situated 20 km from Svedala was used for the calculation. The space heating and the hot tap water heating could not be separated in the charged energy. The average energy use for hot tap water was estimated based on the average charged energy use during the summer months when no space heating is needed, 69,7 kWh/m^2. To minimise the influence of variations, a mean charged energy use for June, July and August for three different blocks including the block studied, and two years, 2000 and 2001, was used. This energy use was slightly higher than the average energy used for hot water in Swedish residential buildings, and can be attributed to the fact that each flat was equipped with washing facilities instead of a common laundry room for the whole block. The shared electricity at Erlandsdal did not contribute to the energy balance of the buildings. The household electricity used during 2000 was obtained from the supplier, Sydkraft AB, and was 13914 kWh, which corresponds to 3,05 W/m^2 and is regarded as a free gain. Gains from people were calculated by estimating a release of 80 W/person and assuming that the tenants were at home half the time. This corresponds to 1,23 W/m^2. These free gains can be compared with the value assumed in the EN-ISO standard described in Section 3.7.3; 5 W/m^2. The calculated results for each year are shown in Table 6.2. The charged energy was 144,5 kWh/m^2, which is 8% more than the calculated 133,7 kWh/m^2 in 2000 and 150,5 compared to calculated 145,6 kWh/m^2, or 4% more in 2001. These results can be regarded as satisfying. The calculation errors are related to tenant behaviour and to technical aspects, such as

- the efficiency of the gas boiler that supplies the space heating and hot tap water. According to the manufacturer, Viessmann, it can be estimated as 1
- the use of hot tap water and true indoor temperature as discussed above
- thermal bridges. A default setting in the programme was used adding 0,03 W/m^2 °C on the U-value of all structures constituting the building envelope except those facing the ground. This accounts, for instance, for a general wall or roof section but not for any thermal bridges related to connections between different parts of the building

Table 6.2 Case study: calculated energy balance (kWh/m²)

	Energy demand					Energy supply			
Year	Transmission	Air leaks*	Ventilation	Hot water	Cooling**	Solar radiation	Gains from electricity	Gains from people	**Heating**
2000	70,8	0*	56,8	69,7	1,7	27,9	26,7	10,8	**133,7**
2001	76,5	0*	60,6	69,7	4,6	28,5	26,7	10,8	**145,6**

** With mechanical exhaust ventilation systems the air leakage only substitutes air coming in through air intakes and is thus not reflected in the energy balance*

*** A maximum temperature +28ºC is used in the calculations since people will presumably open windows when this temperature is reached*

To examine the reliability of the calculations in more detail, Figure 6.1 shows the calculated and measured energy for space heating and hot tap water month by month. Here calculations and measured values also agrees well, except for March and April 2000, which is probably due to a problem with the reading of charged energy.

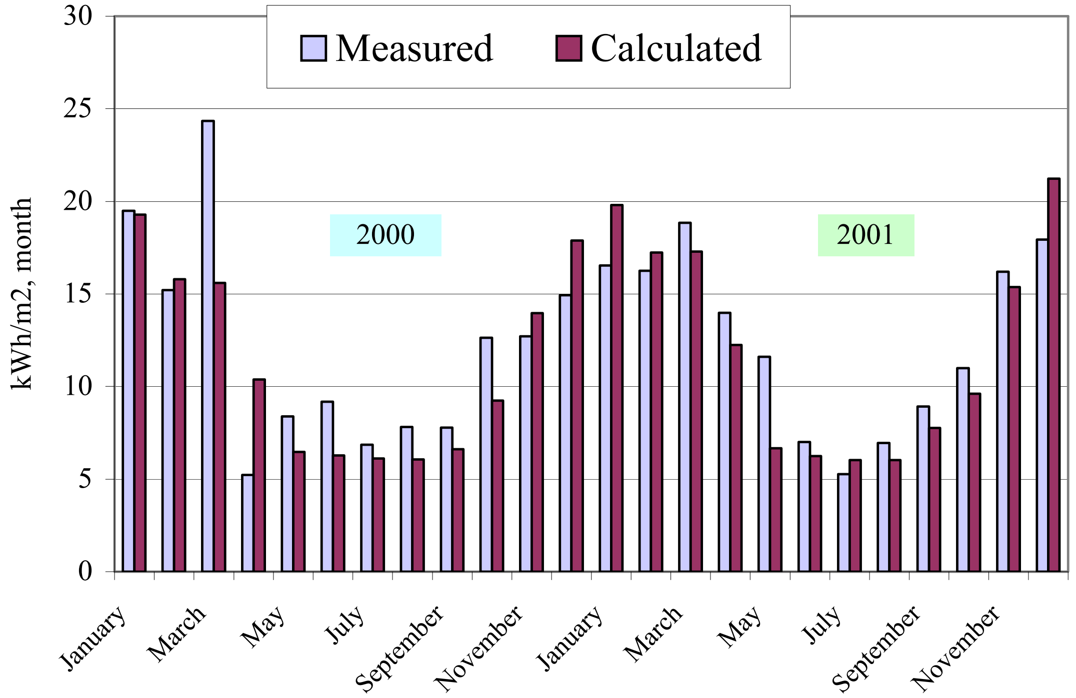


Figure 6.1 Calculated and measured energy use for space heating and hot water in Erlandsdal 2000 and 2001

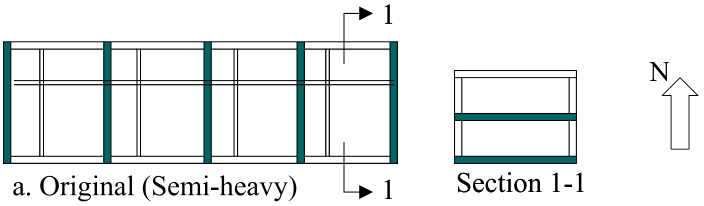
6.3 Parameter study on energy use

To study the effects of changes in the building frame, climate shell and ventilation system, the original building frame of the case study was compared with two alternative types according to Figure 6.2 and Table 6.3.

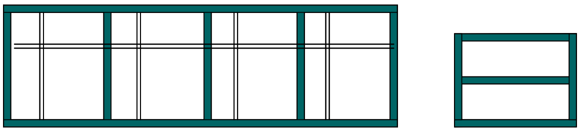
Table 6.3 Parameter study

Ventilation system/Type of building frame	Original	Heavy	Light
Mechanical exhaust. AL*=1,6. 80% of window area facing north and 20% south	A1N	B1N	C1N
Mechanical exhaust. AL*=1,6. 20% of window area facing north and 80% south	A1S	B1S	C1S
Balanced ventilation. AL*=1,6, 20% of window area facing north and 80% south	A2S	B2S	C2S
Balanced ventilation. AL*=0,8, 20% of window area facing north and 80% south	A3S	B3s	

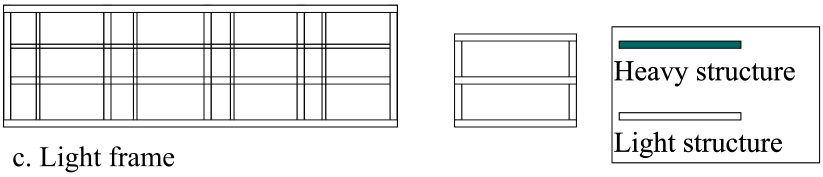
** AL = Air leakage through component at 50 Pa pressure difference measured in* $m^3/m^2,h$.



a. Original (Semi-heavy)



b. Heavy frame



c. Light frame

Figure 6.2 General layout of three different frames

For each case, two different types of ventilation systems were studied; mechanical exhaust ventilation as in the original building, and balanced ventilation with heat recovery. According to the orientation of the original building, 80% of the window area faced directly north and 20% south. An opposite distribution was tested to study the effect of solar radiation. Details regarding structures and energy related aspects are tabled in Appendix C. Results of energy balance calculations are presented in Table 6.4, below and in detail in Appendix C.

Table 6.4 shows the energy use, impact on annual costs, socio-economic costs and present value of costs, at different energy cost levels, for the alternatives examined in the parameter study. The socio-economic cost was calculated utilising the emission factors according to Table 6.1. The socio economic prices are according to Table 4.1. Note that this additional cost with regard to environmental aspects is of the same magnitude as the direct cost. Also note that the performance of the cases in group 1 (mechanical exhaust ventilation) should not be directly compared with the results of groups 2 and 3 (balanced ventilation with heat recovery).

Table 6.4 Energy use, Socio economic cost, annual cost and present value

Case *	Energy for space heating (kWh/m², year)	Annual Socio economic cost (Euro/m²)	Annual Cost (Euro/m²)	Present value. (Euro/m²) Increase of energy cost more than inflation		
				0%	3%	6%
A1N	64,0	2,5	3,6	99	214	619
B1N	62,9	2,4	3,5	97	209	607
C1N	65,2	2,5	3,6	100	217	630
A1S	52,8	2	2,9	81	176	510
B1S	51,3	2	2,9	79	171	496
C1S	54,8	2,1	3	84	182	529
A2S	31,1	1,2	1,7	48	104	301
B2S	29,9	1,2	1,7	46	100	289
C2S	32,7	1,3	1,8	50	109	317
A3S	29,4	1,1	1,6	45	97	282
B3S	28,8	1,1	1,6	43	94	273

* *Cases according to Table 6.3 A: original; B: heavy structure; C: light structure.*

The heavy building (B) requires 4% (Comparisons B1N-C1N), to 8% (Comparisons B1S-C1S) less bought energy for space heating compared to the light (C) structure, due to thermal inertia. This is in line with the results presented by Akander (2000), who reports a difference of 5%. Note, however, that the space heating only represents about 30-50% of the total annual energy use in modern multi-dwelling buildings. Tapwater heating and electricity for lighting and appliances, constitute the rest of the energy use. Air tightness only affects the energy balance in a balanced ventilation system, since with mechanical exhaust ventilation, air leaks only substitute air coming in via air intakes. Comparing the very tight B3S with the normal tightness B2S, the difference in annual energy use is 3-4%. The simulations indicate that, from the annual cost perspective, the impact of differences with regard to energy use between the alternative structures is small, 0,1 to 0,2 Euro/m², which should be viewed in relation to the average heating cost of 7 Euro/m² in modern Swedish multi-dwelling buildings (SCB, 2000). However, as regards life cycle costs the difference can be regarded as significant, ranging from 8 to 11 Euro/m² due to thermal inertia alone and as much as 15 Euro/m² for the combined effect of thermal inertia and air tightness (Comparison C2S to B3S). These figures refer to an energy cost increase of 3% above inflation. This can be viewed in relation to the difference in production costs between the concrete and timber frame in Erlandsdal, which was 9,5 Euro/m² (Persson, 1999).

The orientation of windows in the building with regard to the solar radiation was studied by turning the Erlandsdal building. In Figure 6.3, the effect on annual energy use for space heating is displayed. The proportion of window area in this particular building is 80% north, 20% south, and no windows to the east and west, corresponding to the orientation defined as north in Figure 6.3. The dotted line indicates the energy use depending on the orientation of the building. North in the chart is the original situation. The building is rotated in steps of 45º. Figure 6.3 shows that there is a substantial benefit as regards required energy for space heating to be exploited by optimal orientation of windows in this type of building. This may, however, be contradictory to thermal comfort during the summer, a factor that is discussed in Section 7.3.

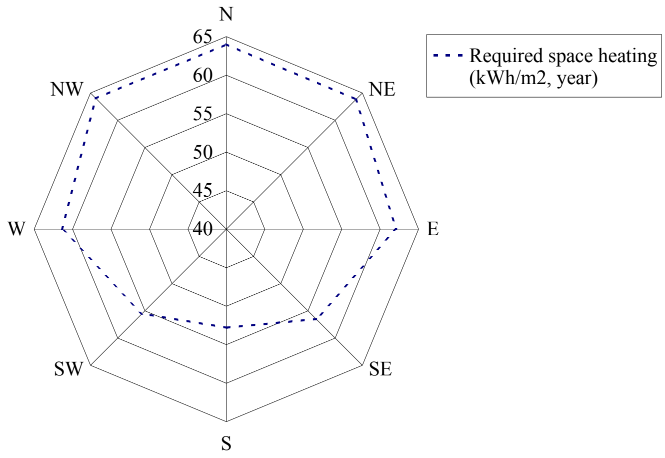


Figure 6.3 Energy need. Dependence on orientation of windows

6.4 Energy use - conclusions

The energy required for space heating is dependent on several parameters such as insulation, the ventilation system, air tightness, thermal mass and the orientation of the building. It can be predicted with reasonable accuracy using commercial dynamic energy balance programmes. In the parameter study, thermal mass influenced energy use for space heating by 4-8%, air tightness by 4% and orientation of windows by as much as 20%. Small differences as regards annual energy use were shown to be significant in the life cycle perspective.

7. INDOOR ENVIRONMENT SURVEY AND PARAMETER STUDY

7.1 General

The indoor environment is a fundamental property of buildings. Methods to deal with this aspect are discussed in Section 3.6 for acoustics and in Section 4.7 for the indoor air climate. In this chapter a typical modern concrete multi-dwelling building is examined using the ‘SABO-questionnaire’ (Engvall and Norrby, 1992). Apart from the purpose to study the indoor environmental performance of a normal modern concrete multi-dwelling, this was done to examine the applicability of the method. Furthermore, a parameter study was done carried out on indoor temperatures during the summer with regard to thermal capacity and the orientation of windows.

7.2 Indoor climate survey

The indoor climate survey comprised the entire set of nine, except for orientation, identical buildings with a total of 64 flats in Erlandsdal, Svedala. After sending out two reminders, an answering rate of 88% was achieved.

The complaint profile for indoor climate is displayed in Figure 7.1, and for health aspects in Figure 7.2.

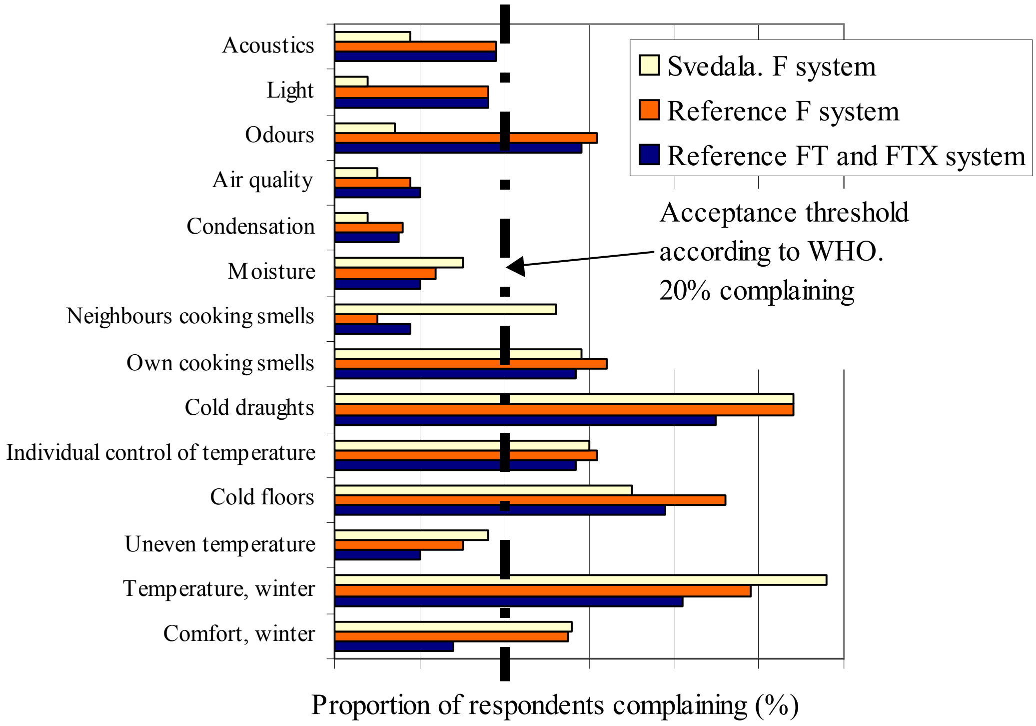


Figure 7.1 Indoor climate complaint profile for Erlandsdal, Svedala

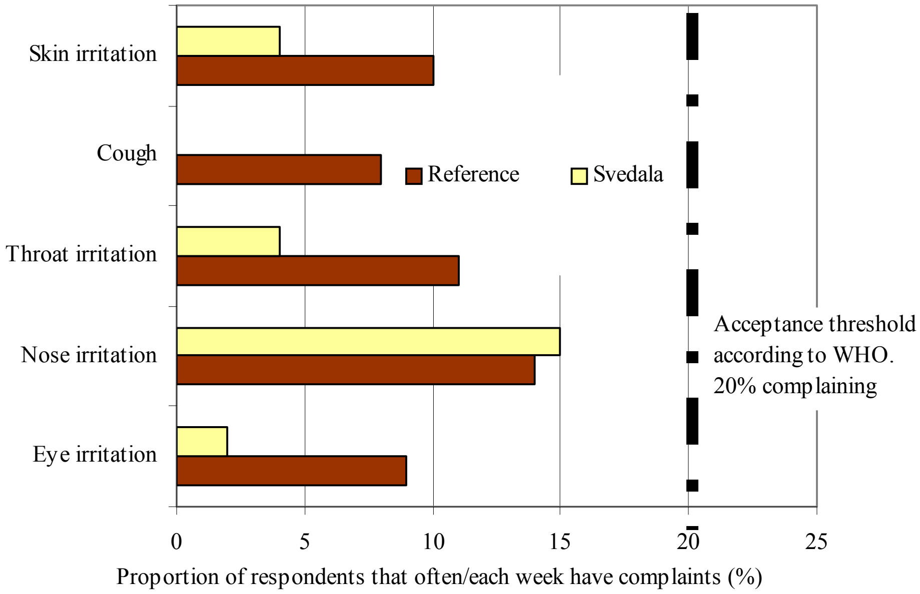


Figure 7.2 Health complaint profile Erlandsdal, Svedala

The following aspects were perceived significantly (95% CI) better than the reference of 10000 households in the Stockholm area; odours in general, light, acoustics and sick building symptoms. The following aspects were reported worse than the reference; cooking smells from neighbours and temperatures during the winter. The perception of temperature during the summer, air quality and humidity did not deviate significantly from the reference.

Apart from the 45 specific questions in the questionnaire, the respondents were invited to include any other comments. A recurring remark deals with cold draughts during the winter. A thermometer was distributed along with the questionnaires. The average indoor temperature recorded was close to 22ºC. This temperature was used for the energy balance calculations. With regard to the perceived indoor air quality and health related issues, the building and its service systems appear to function well. The survey, however, indicates that the mechanical exhaust ventilation system /F System/ is a weak spot. Cold air from the intakes above the windows generates dissatisfaction with the thermal comfort during the winter. To counter the cold draught, the air intakes have been blocked by the tenants in several cases. Blocked air intakes may result in opposite air streams through the ventilation system, which in turn explains why the smells from the neighbours cooking may spread. Mechanical exhaust ventilation systems in general behave less satisfactorily than balanced ventilation systems /FT- and FTX ventilation/, when it comes to thermal aspects, compare Figure 2.3.

The method was easy to apply and the results gave valuable information on the performance of the building and its service system.

7.3 Parameter study on indoor temperatures during summer

Thermal storage also has an impact on indoor temperatures, and thus thermal comfort. The indoor temperatures could be assessed using the energy balance program (VIP+, 1994). The number of days with indoor temperatures above 28ºC was used as indicator. By comparing the original structure (a) with the heavy (b) and the light (c), according to Figure 6.2, it was found that 36, 12 and 60 days respectively had an indoor temperature exceeding 28ºC. The main proportion of window area in this particular building was; 80% to the north, 20% to the south and no windows to the east and west, according to the original building. If the building is rotated so that the main proportion of windows face south, the number of days with high indoor temperatures increases significantly. Figure 7.3 shows the effect of thermal mass and the orientation of windows on indoor temperatures during summer. Building frames are according to Table 6.3.

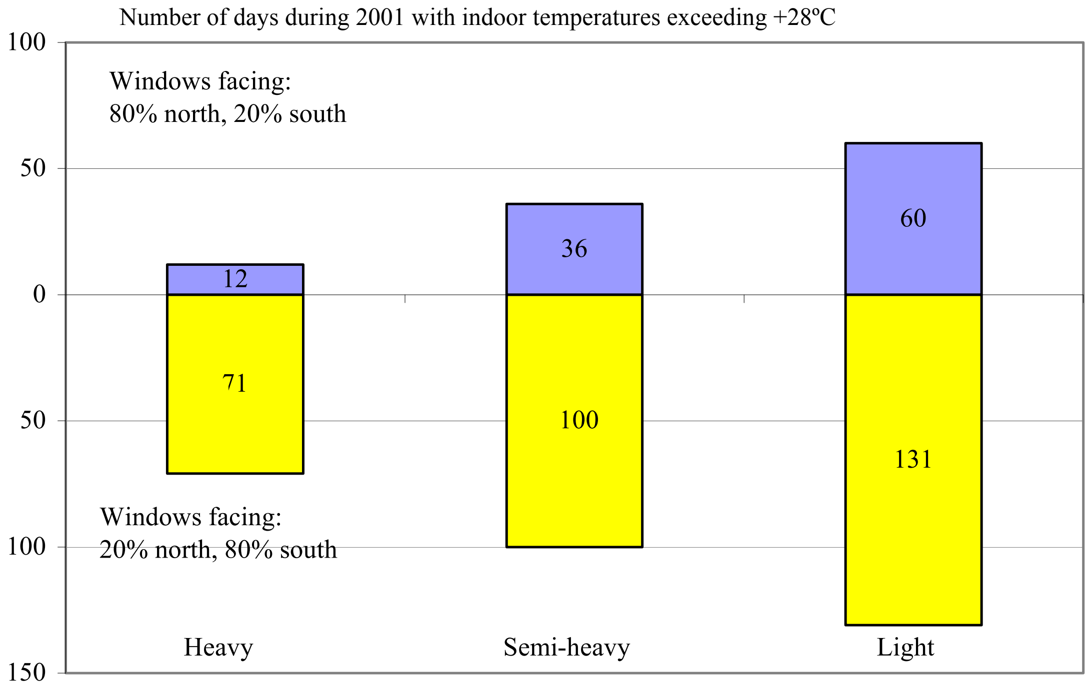


Figure 7.3 The effect of thermal mass and the orientation of windows on indoor temperatures during the summer. Blue bars for windows primarily facing north.

In Figure 7.4, where the impact of window orientation is presented, the dotted line indicates the number of days with indoor temperatures exceeding 28ºC depending on the orientation of the building. Indoor temperatures were calculated for the building is rotated in steps of 45º.

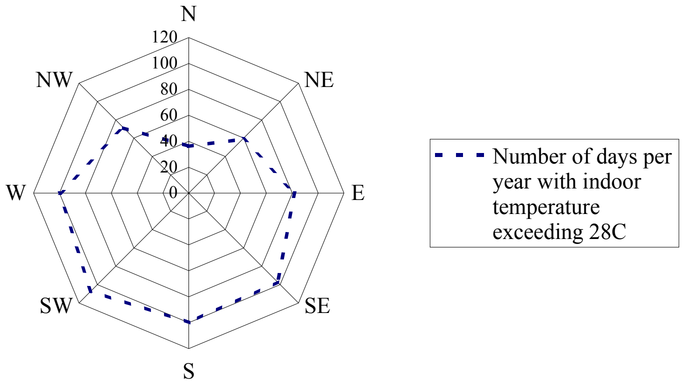


Figure 7.4 Impact on indoor temperatures by orientation of windows. The proportion of windows is 80% towards the direction in the radar chart and 20% in the opposite direction.

7.4 Indoor environment - conclusions

The indoor climate questionnaire is a very good tool for collecting feed back on the performance of the building and its service system. Any particular problems related to, for instance, details that are deficient due to design or execution mistakes are also traced. It would be advisable to conduct this kind of survey one or two years after the completion of all larger projects.

The modern concrete building examined, performed well compared to the reference, both with regard to health and comfort issues. The problems encountered as regards temperature comfort during cold climatic conditions were related to the type of ventilation system.

With a holistic design procedure, where the designers of heating and ventilation systems, structural designers and architects coordinate their efforts, a healthy and comfortable indoor climate can be achieved and energy efficiency can be obtained. This is exemplified in the parameter study on indoor temperatures in relation to the type of building structure and orientation of windows.

8 EXAMPLE - CHOICE OF ADVANTAGEOUS ALTERNATIVE

8.1 ILCD and multiple criteria decision-making - general

This chapter presents an example of the application of principles for multiple criteria decision-making in buildings. A simplified MADA approach (ASTM, 1998), compare section 4.8, is outlined. A spreadsheet tool was developed to aid calculations. MADA is applied to select the preferable choice among a finite set of alternatives for which life cycle appraisal, or traditional design tools, have been applied to assess selected aspects.

8.2 Example

The example is based on the evaluation criteria included in the contest initiated by the Swedish Delegation on Building Costs (BKD, 2000). The purpose of the contest was to promote cost effective new multi-dwelling buildings. The quality criteria stated in the tender documents were evaluated with the following ranking of importance; 40% economy, expressed as rent, 20% indoor climate, 20% functional quality, 20% ecology and resource use. In the contest each attribute was divided into several detailed sub-attributes and requirements.

This example presents how MADA can be used, in principle, for the ranking of alternatives in this particular case. The example is a simplification were only one group of sub-attributes is considered. Three different alternative proposals are compared: **α, β** and **γ**. Life cycle costs and energy use have been calculated for the alternatives and are compiled in Table 8.1, together with data for the other attributes for each alternative design. The example presents in detail a way of integrating parameters measured by numerical units, classes and verbal expressions.

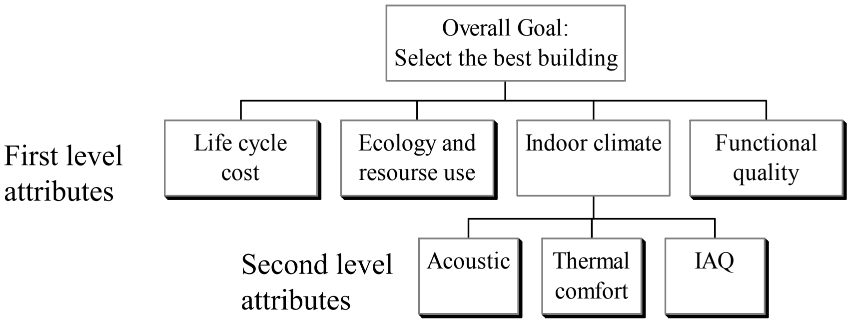


Figure 8.1. Hierarchy for the example with leaf attributes shaded

According to MADA principles, a hierarchy for the selection problem is drawn up, compare Figure 8.1. More than two levels of attributes may be used but according to ASTM (1998) not more than four levels can be treated practically. The next step is to compile a decision matrix covering all attributes, see Table 8.1

The decision matrix is processed with paired comparisons between

- the alternatives for each leaf attribute
- the attributes for each attribute level

Table 8.1 Decision matrix

Attribute		Performance of alternative			
Level 1	Level 2	**α**	**β**	**γ**	Unit
Life cycle cost. 50 years		1766	1777	1768	Euro/m²
Energy use. 50 years		6685	6630	6748	kWh/m²
Indoor climate	Acoustics	B	B	C	Sound Class
	Thermal comfort (indoor temp.)	36	12	60	Days/year >28°C
	Indoor air quality	Very good	Very good	Very good	Verbal
Functional quality*		Excellent	Excellent	Good	Verbal

** In this example expressed as flexibility for future change. This can be conducted with a matrix of paired comparisons as shown in Table 8.2. Values that are expressed in figures can be used directly, but verbal expressions and classes need to be digitalized.*

Table 8.2 Matrix of pairwise comparisons

		Alternative or Attribute			
Alternative or Attribute		1	2		n
	1	1	Desirability of 1 over 2		Desirability of 1 over n
	2	Desirability of 2 over 1	1		
				1	
	N	Desirability of N over 1			1

To simplify the procedure, it is desirable to use a predefined set of verbal expressions in the comparisons, for instance a sequence such as ‘acceptable, fair, good, very good, excellent’ for comparison of performance, or ‘equal, somewhat more important, more important, very much more important’ for comparisons of attributes. These verbal expressions, as well as classes, such as sound classes A, B, C and D as presented in section 3.6, can thus be dealt with using matrices of paired comparisons. Table 8.2 presents a matrix of pairwise comparisons. Note that values on opposite sides of the diagonal are inverted. Tables 8.3 and 8.4 show the digitalisation and comparisons of verbal expressions and performance classes. Any number of alternatives or attributes can in principle be treated with the matrices. 10 might, however, be regarded as a practical maximum.

Table 8.3 Digitalisation and pairwise comparisons of verbal expressions

		Digitalised values				
		5	4	3	2	1
		Verbal expressions				
		excellent	very good	Good	fair	acceptable
5	excellent	1	1,25	1,67	2,5	5
4	very good	0,8	1	1,33	2	4
3	good	0,6	0,75	1	1,5	3
2	fair	0,4	0,5	0,67	1	2
1	acceptable	0,2	0,25	0,33	0,5	1

Table 8.4 Digitalisation and pair wise comparisons of performance classes

Digitalised values				
	4	3	2	1
Performance class				
	A	B	C	D
A	1	1,33	2	4
B	0,75	1	1,5	3
C	0,5	0,67	1	2
D	0,25	0,33	0,5	1

The procedure in the following example is a simplification of MADA practice using only the first row of a matrix of pairwise comparisons. The following two conditions are set

- in all comparisons, one alternative, in this example '**α**', is appointed as the reference
- in all comparisons, a quotient greater than 1 represents a positive relation. Thus in Table 8.4, class A is better than class B according to the quotients in the first row. If this is not the case, the inverted value should be used.

Comparisons of alternatives for each leaf attribute. A leaf attribute is an attribute with no sub-attributes. For details, see Appendix E:

Life cycle cost for alternatives **α,β,γ** according to Table 8.1; 1766, 1777, 1768.

The first row of the matrix of comparison gives; 1,1766/1777, 1766/1768 i.e. 1, 0.993, 0.999. Since higher costs renders quotients less than 0, these should not be inverted.

Life cycle energy use for alternatives **α,β,γ** according to Table 8.1; 6685, 6630, 6748. The first row of the matrix of comparison gives; 1,6685/6630, 6685/6748; i.e. 1, 1.008, 0.991. Since higher energy use renders quotients less than 0 these should not be inverted.

Acoustics for alternatives **α,β,γ** according to Table 8.1; Sound class B, B, C of available classes A,B,C,D. The first row of the matrix of comparison gives; 1,1,0,67. Since lower sound class renders quotients less than 0, these should not be inverted.

Thermal comfort for alternatives **α,β,γ** according to Table 8.1; 36, 12, 60 days
The first row of the matrix of comparison gives; 1,36/12, 36/60 i.e. 1, 3.0, 0.6. Since more days with excess temperature renders quotients less than 0, these should not be inverted.

Indoor air quality for alternatives **α,β,γ** according to Table 8.1; very good, very good, very good. The first row of the matrix of comparison gives; 1, 1, 1.

Functional quality for alternatives **α,β,γ** according to Table 8.1; excellent, excellent, good. The first row of the matrix of comparison gives; 1, 1, 1,67. Since better verbal expression renders quotients less than 0, these should be inverted to 1, 1, 0,60

Comparisons of attributes at each attribute level:

Relative desirability of attributes at level 1 according to BKD (2000): 40% Economy expressed as rent, 20% indoor climate, 20% functional quality, 20% ecology and resource use. The first row of the matrix of comparison gives; 1, 2, 2, 2. Since lower desirability renders quotients greater than 0, these should be inverted to 1, 0.5, 0.5, 0.5 and normalized to 0,4, 0,2, 0,2, 0,2.

Relative desirability of attributes at level 2 here defined as 40% on acoustics, 20% on thermal comfort and 40% on IAQ. The first row of the matrix of comparison will thus be; 1, 2, 1. Since lower desirability renders quotients greater than 0, these should be inverted to 1, 0.5, 1 and normalized to 0,4, 0,2, 0,4.

Next the aggregated value of each alternative for each group and level of attributes is calculated starting from the bottom of the hierarchy according to Figure 8.1.

Aggregated values for all attributes, and the final ranking between alternatives are shown in Table 8.5. In this example, the preferred alternative is **β**. Note that the figures for alternative **α** show the relative desirability allocated to each particular attribute. Detailed calculations are presented in Appendix E.

Table 8.5. Final ranking of alternatives in the example

	Alternative **α**	Alternative **β**	Alternative γ
LCC	0,40	0,397	0,400
Energy use	0,20	0,202	0,198
Acoustics	0,08	0,080	0,053
Thermal comfort	0,04	0,120	0,024
IAQ	0,08	0,080	0,080
Functional quality	0,20	0,200	0,120
Sum	**1**	**1,08**	**0,87**

8.3 Comments to the methodology

The analysis is sensitive to the relation between the digitalized values attached to the verbal expressions and classes. For example, in Table 8.4, the relation between two neighbouring classes varies depending on where in the matrix they are. Thus, C is desired twice as much as D, but A is desired 1,33 times B. Other relationships can be chosen, for example if the relationship between neighbours is equal, the digitalized values should be 8, 4, 2, 1, compare Table 8.6. This will affect the result of the calculation. The crucial factor is the desirability for row 1 over column n, compare Table 8.2.

When numbers are used the range has a large influence. In the example the impact of thermal comfort is very pronounced while LCC is not. It may be advisable to arrange attributes such as thermal comfort according to table 8.3, to avoid this difficulty. In this case for instance Fair for **α** (36 days), Excellent for **β** (12 days) and Acceptable for **γ** (60 days).

Table 8.6 Digitalisation and pairwise comparisons of performance classes with alternative mutual relationship

Digitalised values				
	8	4	2	1
Performance class				
	A	B	C	D
A	1	2	4	8
B	0,5	1	2	4
C	0,25	0,5	1	2
D	0,125	0,25	0,5	1

It is very important to be aware of the sensitivity of the method in this respect. ILCD can also be performed without the application of MADA or similar methods. In such a case, the requirements of the building can be defined, and the evaluation of alternatives be done simply by comparing life cycle costs. The environmental perspective can be taken into account by calculating and adding socio-economic costs according to the example given in Section 6.3.

9 DISCUSSION ON THE INTRODUCTION OF ILCD IN PRACTICE

9.1 ILCD - advantages and barriers

The impact of the built environment, and in particular the operational phase, regarding for instance energy use, waste streams and economy implies that buildings should be optimised with regard to their life cycle performance. BKD, (2000), states that: '*projects should be procured on life cycle costs rather than production costs'*.

The prime obstacle to life cycle optimisation is possibly the fragmented building process. The designer and/or producer may lack interest in, or knowledge about the user phase. The structural designer may not collaborate with the heating and ventilation experts. The acoustic designer may be introduced late in the design process when effective acoustic solutions may no longer be possible. For the frontrunners, ILCD provides competitive advantages. For the facilities owner and user of the building, the advantages are obvious as they also are for actors engaging in design, build and operating contracts. Also the pure producer can benefit from the systemisation that follows from life cycle design. The public interest is also obvious, in that ILCD is an instrument that supports sustainable development.

9.2 Introduction of ILCD methodology in the design process

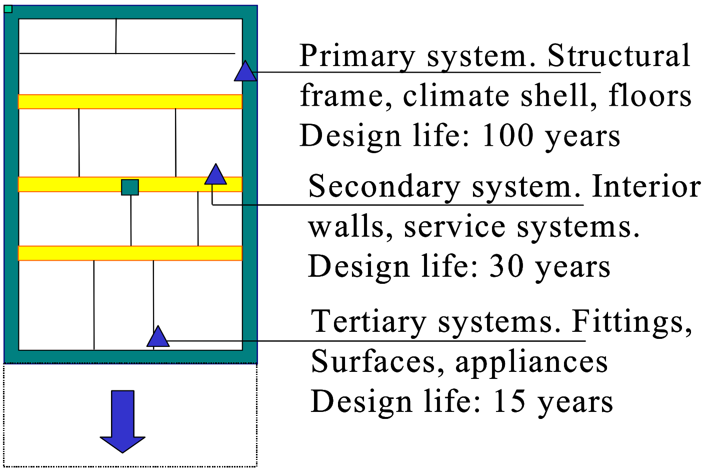
Life cycle design can be introduced into the regular design process by expanding 3-dimensional IT design systems with life-cycle design tools. Life cycle cost, acoustic performance and energy use can be estimated when a 3-dimesional model of the building has been defined. Modern IT systems facilitate design in different levels of detail; from sketching in the early project phases to detailed construction drawings. Life cycle design tools can also be applied from the earliest design phase, and with increased level of detail, follow the design process. Furthermore, the life cycle appraisal systems could also in a logical way be utilised in the facilities management phase. Feedback of information to the design team should then be secured, and the often debated link between designer, supplier, producer, client and user would be reinforced. Thus the inconvenience of changing and introducing new design routines is compensated by improvements to the entire building process, and in the end, the building.

General ILCD for buildings can be conducted with tools and input data that are available. The method is suitable for applications representing a large number of buildings, for the development of type houses or for very large projects. A simplified ILCD approach adopted for a particular type of building can be used on a regular basis in the early design phase of ordinary buildings to assess alternative designs. A tool kit for simplified ILCD of Swedish concrete multi-dwelling buildings can, for example, be composed with the following software;

- Energy balance and thermal comfort: VIP+ (1994)
- Acoustic design: BASTIAN® (1996) for detailed calculations or 'The Concrete Bank' (SFF, 2000) for standard structural design solutions
- LCC-tool: Spreadsheet tool developed in this work using the maintenance database according to SABO (1999)
- Global environment: Spreadsheet LCA tool for energy use in buildings developed in this work using the databases for energy and transport according to CIT (2000)
- Simplified tool for multiple attribute decision-making according to spreadsheet tool developed in this work

9.3 Implications on the product - the residential building

A building consists of several systems, structures and components that have different design lives. Components that constitute the building framework will last as long as the building. It is thus for residential buildings typically from 50 to 100 years, or more. Other components will be exchanged one or more times during the life cycle of the building, either because they become obsolete, or because their longevity is limited. Furthermore, modifications may be initiated due to changes in the use of the premises, required sizes of the flats, or the number of rooms. In order to facilitate these changes and to optimise components and systems with regard of durability, a modular design approach can be applied. Sarja (2002, p 17) discusses the classification of building modules into target life classes so that the components and systems can be optimised as regards life cycle costs and environmental impact. In Figure 9.1, the principle for modular design presented with regard of target life is presented. Concrete structures are mostly found in the primary system, and can be provided with sufficient durability, according to section 3.8, for life spans of 100 years or more.



Prepared extension

Figure 9.1 Plan of building with classification of components and systems in target life modules.

In Figure 9.2 some implications on durability and recycling aspects are shown. These characteristics should be adapted to the target service life in order to optimise life cycle costs and environmental aspects. For the long life component durability is more important, while aptitude for recycling is less crucial.

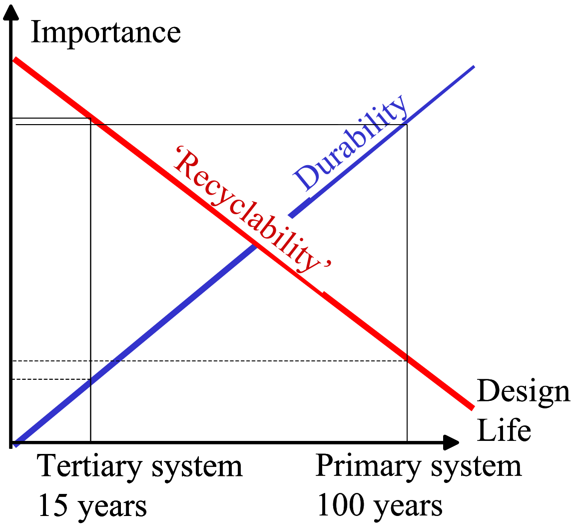


Figure 9.2 Implications of design life on importance of durability and aptitude for recycling, which should be considered with whole life appraisal

An actual example of how life cycle flexibility might be more or less facilitated is presented in Figure 9.3. Here, the electrical service installations in two, basically identical buildings, from the field study on life cycle costs in Chapter 5: Joggaren and Terränglöparen are shown. In this case, the production method has influenced the design. The building on the left is a precast structure in which, for systematic reasons the conduits are concentrated. The building to the right is a cast in situ structure in which the conduits were optimised to go the shortest way. It is rather obvious what solution would be the easiest to maintain, change and in the end recycle. It should be noted that there is no reason why, in the cast in situ building, the installations should not be organised in the similar systematic way, as in the precast building.

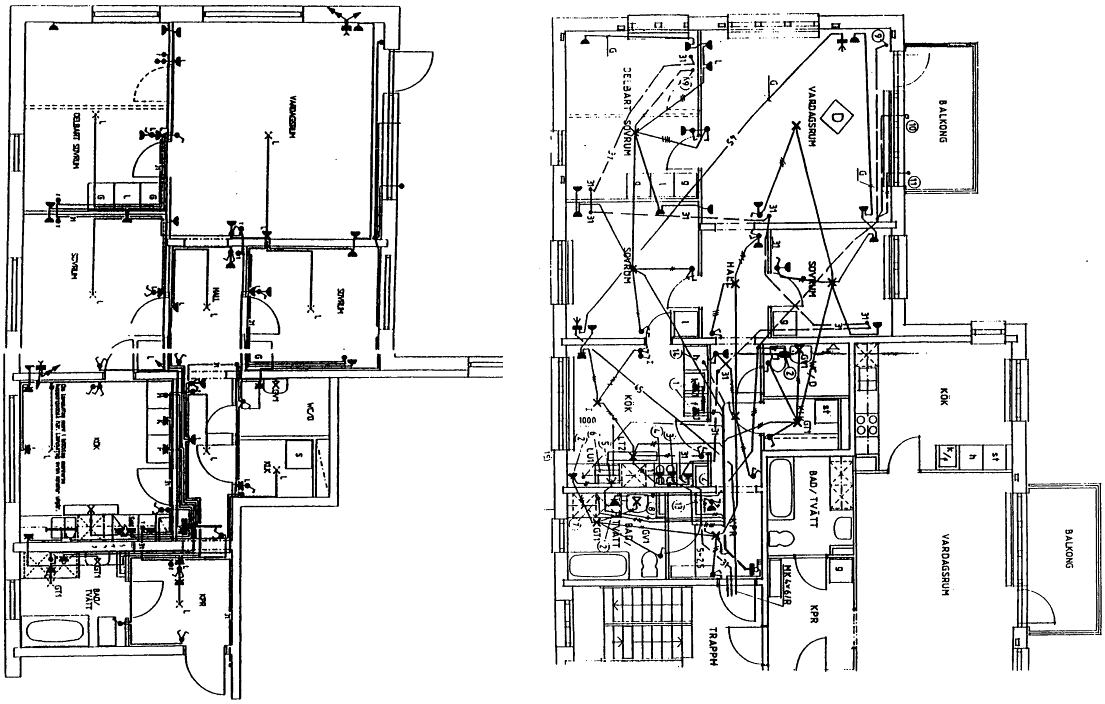


Figure 9.3 Different solutions regarding electrical installations (Paus, 1996)

Open Building, 'OB' is a design approach that supports strategies for programming, design, production planning and facility management in organising buildings physically into different layers. These extend from urban planning, over the building frame 'support', to fit-outs of components and systems, 'infill', and finally furnishings, fixtures and equipment, 'FF&E'. The key features are design for flexibility and appropriate longevity and disentanglement of systems. The modular approach of OB allows for systematic optimisation of the target service life, life cycle cost and environmental aspects of different parts of a building (Sarja, 2000 and Sarja, 2002 p 30). One important idea of OB is what can be referred to as *mass-customisation*. During the 1960s, the effectiveness of the production of multi-family dwelling buildings in Europe rose dramatically. This development was, however, founded on an extreme production orientation with large-scale projects and high repetitiveness, compare Figure 3.10. OB promises similar productivity but irrespective of project size and with a high degree of architectural freedom.

OB promotes competition between different suppliers since the components are designed and purchased as modules that in principle are exchangeable.

A current example of OB from Japan (Yashiro, 2000) is a system for up to seven-storied, concrete multi-family dwelling buildings. The building frame 'support' consisting of concrete columns and beams is designed for 200 years, which is extremely long for Japanese conditions. In this case, however, considered as reasonable in the context of assuring sustainability requirements. The spatial composition of the interior is highly adaptable, and even certain concrete floor slabs may be removed. All technical service systems are easily accessible for exchange or repair.

Kendall (2000) has presented a comprehensive overview on the theory and practical application of the OB-concept applied to residential buildings. The examples indicate that there is a critical, and sometimes rather diffuse line, between *mass-customization* and *mass-production,* and that care must be taken to avoid repeating the over-industrialization, typical of the large-scale residential projects of the 1960s. Many architects and city planners are profoundly sceptical about construction-kit systems that are geared primarily towards satisfying the requirements of the production phase. Flexibility in design as regards planning and aesthetics and between and in projects, is crucial to the implementation of OB.

10 FUTURE WORK

A demonstration concrete multi-dwelling building could be designed based on whole life considerations such as life cycle cost and energy use. The building could be optimised with regard to a defined priority of the different characteristics important for a dwelling building based on design tools and data developed during the first phase of the project. Environmentally related attributes and flexibility in use are of particular interest. Looking at the multi-dwelling building of the future, one of the most important questions is how to reduce energy requirement for the operational phase, while safeguarding the indoor climate. Concrete provides a good base for this development. Further parameter studies on different technical solutions with regard to building frame, climate shell and ventilations systems should be done to examine how cost effective and robust technical solutions for low energy housing can be obtained. Special attention should be paid to the particular possibilities regarding the production and functional quality of a state-of-art concrete building frame.

The *Open Building* concept is a modular, systematic approach to adopting and organising the building, which fits well with the principles of ILCD. Experience from successful applications of Open Building in e.g. Finland, Japan and the Netherlands should be further explored and adapted in the demonstration. project mentioned above.

On the methodological side, the simplified ILCD tool outlined in this thesis could be further developed to facilitate the administration of input data. A parallel possibility is to expand a suitable 3-D design system, primarily with a life cycle appraisal tool. The link to facilities management that could be opened is of particular interest. Multiple attribute decision-making should be further examined and tried out in practise. It can probably be catered for efficiently without having to integrate it into the design programmes.

11 CONCLUSIONS

Important attributes of multi-dwelling buildings and the significance of concrete

A building must satisfy a number of attributes. Some of the attributes are variables that can be expressed in performance classes, for instance, sound insulation. Others, such as safety are unconditional requirements. Finally, economy and the environment are expenses that should be minimised over the life cycle, in principle depending on the designer's skill in meeting the functional attributes of the building. Economy and environmental performance can thus be referred to as consequential or resulting attributes.

The basic characteristics of concrete are high density, formability and its inorganic composition. Density can sometimes be disadvantageous, for instance with regard to costs for foundations when friction piles are used, or when a building is going to be extended vertically, and loads on the existing building must be minimised. Beneficial concrete properties for dwelling buildings are; load carrying capacity, fire and moisture safety, sound insulation, thermal mass that can provide comfortable indoor temperatures and decrease the required energy for heating, durability and robustness in a broad sense. Concrete is thus a multifunctional building material that relates to most of the important attributes of the building. If the properties of concrete and its interaction with the adjoining materials and systems are understood and observed, the building can be optimised over the life cycle according to priorities defined for the specific case.

Identification of suitable life cycle appraisal methods and input data

Methods and input data to predict the life cycle performance with regard to the resulting attributes economy (life cycle costing) and environmental performance (life cycle assessment), are available.

Conventional LCC calculations estimating present values, or annualised costs, can be applied in the design phase to evaluate different designs of entire buildings or single systems or components. In the latter case, special care must be taken to trace any secondary effects with regard to costs that may occur. Reliable input data, for instance with regard to maintenance costs for components and materials can be obtained from the facilities management sector. For time perspectives relevant for buildings, the choice of interest rates for calculations can be based on average rates for a long previous period. The relation between the price increase of a specific item and inflation can be dealt with using sensitivity analysis.

A complete LCA of a building is still a demanding task, since the necessary quantitative environmental data with regard of production, use and final disposal of materials and systems is not yet readily available for all the components that constitute a building. LCA is, therefore, not yet applicable in the ordinary design process. LCA is, however, an adequate tool to guide environmental improvement or to establish quantitative environmental product declarations of single products or for systems or type buildings. Energy use during the operational phase has been identified as the, by far, most critical global environmental and resource use aspect of buildings. Operational energy demand can thus be applied as a proxy for the environment. Commercial software for the prediction of energy use with appropriate accuracy is available. A comparative study indicated deviations between calculated and charged energy use of less than 10%. If the program is used for optimisation, it is crucial that it is capable of appreciating building physical related aspects, such as orientation of windows, airflows and thermal capacity. The time step in the calculation should thus not be greater than 1 hour as the dominant thermal cycle of a building is 24 hours. With modern PCs this is no problem. These energy balance programs can also indicate indoor temperatures, which is an important comfort aspect.

In the future when reliable environmental product declarations will be available, LCA methodology may be used in the design phase to compare environmental life cycle performance of different alternatives. However, energy use during the operational phase will then still be the key environmental issue, and results from energy balance calculations will be used as input in the LCA.

Potential improvements in the application of the life cycle appraisal methods

About half the life cycle costs refer to the operational phase. Periodic maintenance, heating and care-taking are the most important items as regards operational costs and they are all dependent on the design of the building. With regard to life cycle costs a parameter study on one existing building with a theoretical alternative showed slightly higher production costs for the alternative with concrete frame and brick façade /4%/ compared to one with a wooden frame with wood panel façade. However, looking at life cycle costs, this is balanced out by lower costs for periodic maintenance, insurance and energy. The differences are rather small, which can be explained by the fact that the whole building including all parameters and systems that were equal in both alternatives were included in the calculations. In this comparison, differences with regard to functional performance, such as flexibility and acoustics were not taken into account. If a single component or system is analysed, here illustrated with the alternative façades, the differences become more distinct. However, when evaluating single components there is a risk of missing indirect consequences, which is why LCC calculations of the entire building are preferable.

A parameter study on energy use for space heating in a multi-dwelling building in southern Sweden indicated that thermal mass, air tightness and the orientation of windows may contribute with energy savings in the range of 0-8%, and somewhat more for solar radiation. This has a limited effect on the annual costs of the building. In the life cycle perspective, however, the differences are significant, both with regard to costs and environmental performance.

Application of ILCD in concrete multi-dwelling buildings

The essence of ILCD is to apply two important perspectives that are only to a limited extent covered by current practice when designing houses;

- Life cycle. Meaning that the cost of the designed building with regard to economy, as well as environmental impact is predicted not only with regard to the production, but also for the entire life cycle
- Integrated. Implying that a holistic view is pursued where ideally, interaction between different parameters and attributes are considered, but also special procedures are applied to optimise a set of different variables that may be measured both in quantitative and qualitative terms.

ILCD consists of a combination of traditional design tools, tools for life cycle appraisal, and methods for multiple criteria decision-making. It can be used in different levels of detail depending on the application. The most important design principle is modularisation, whereby components and systems are classified and optimised according to the target service life.

In order to test the practical applicability of ILCD, a simplified version was employed ranking three alternative designs with regard to economy, energy use and a few selected indoor environment parameters. The example indicates the possibilities of the method. The user must, however, be aware of the sensitivity of ranking according to multi-attribute decision-making theory. Simplified ILCD based on LCC and socio-economic calculations can be used as an alternative to multi-attribute decision-making.

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APPENDIX A. THE EU ESSENTIAL REQUIREMENTS

The EU Building Product Directive 89/106/EEC of 21 December 1988 states six essential requirements that, subject to normal maintenance, should be satisfied for an economically reasonable working life.

1. Mechanical resistance and stability
The construction works must be designed and built in such a way that the loadings that are liable to act on it during its constructions and use will not lead to any of the following:
(a) collapse of the whole or part of the work:
(b) major deformations to an inadmissible degree;
(c) damage to other parts of the works or to fittings or installed equipment as a result of major deformation of the load-bearing construction;
(d) damage by an event to an extent disproportionate to the original cause.
2. Safety in case of fire
The construction works must be designed and built in such a way that in the event of an outbreak of fire:
- the load-bearing capacity of the construction can be assumed for a specific period of time,
- the generation and spread of fire and smoke in the works are limited,
- the spread of the fire to neighbouring construction works is limited,
- the safety of rescue teams is taken into consideration.
3. Hygiene, health and the environment
The construction work must be designed and built in such a way that it will not be a threat to the hygiene or health of the occupants or neighbours, in particular as a result of any of the following:
- the giving-off of toxic gas,
- the presence of dangerous particles or gases in the air,
- the emission of dangerous radiation,
- pollution or poisoning of the water or soil,
- faulty elimination of waste water, smoke, solid or liquid wastes,
- the Presence of damp in parts of the works or on surfaces in the works
4. Safety in use
The construction work must be designed and built in such a way that it does not present unacceptable risks of accidents in service or in operation such as slipping, falling, collision, burns, electrocution, injury from explosion.
5. Protection against noise
The construction works must be designed and built in such a way that noise perceived by the occupants or people nearby is kept down to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.
6. Energy economy and heat retention
The construction works and its heating, cooling and ventilation installations must be designed and built in such a way that the amount of energy required in use shall be low, having regard to the climatic conditions of the location and the occupants.

APPENDIX B. LCC TOOL. INPUT DATA AND RESULTS

Table B 1. Result sheet. Original design. Erlandsdal

Annual cost and present value. Results

Project:	Erlandsdal original	Net floor area (m2)
Calculation horizon: (years)	60	4032
Unit:	Entire building	
Real interest rate (%):	3,0	

Annual costs. Compilation	Entire building Euro	Price change relative to inflation (%, + over)	Euro per m2 Net floor area
Production	125622	0,5	31,1
Administration	3047	0,5	0,8
Waste	5618	1,5	1,4
bbbbbWater and sewage	13167	0,5	3,2
House tax	20887	0,5	5,2
Common electricity	610	1,5	0,1
Heating	24359	1,5	6,0
Insurance	1253	0,5	0,3
Care-taking	14382	0,5	3,6
Other annual cost 1	3047	0,5	0,8
Other annual cost 2	0	0,5	0,0
Periodic maintenance	38589	0,5	9,6
Value at end	-28552	0,5	-7,1
Total	222028		55,1

Present value compilation			
Production	3882816	0,5	963,0
Administration	94165	0,5	23,3
Waste	221221	1,5	54,9
Water and sewage	406967	0,5	100,9
House tax	645592	0,5	160,1
Common electricity	24035	1,5	6,0
Heating	959264	1,5	237,9
Insurance	38739	0,5	9,6
Care-taking	444515	0,5	110,2
Other annual cost 1	94165	0,5	23,3
Other annual cost 2	0	0,5	0,0
Periodic maintenance	1192732	0,5	295,8
Value at end	-882500	0,5	-218,9
Total	7121711		1766,3

Table B.2 Result sheet. Alternative design. Erlandsdal

Annual cost and present value. Results

Project:	Erlandsdal timber		Net floor area (m2)
Calculation horizon: (years)	60		4032
Unit:	Entire building		
Real interest rate (%):	3,0		

Annual costs. Compilation	Entire building Euro	Price change relative to inflation (%, + over)	Euro per m2 Net floor area
Production	118984	0,50	29,6
Administration	3047	0,50	0,8
Waste	5618	1,50	1,4
Water and sewage	13167	0,50	3,2
House tax	20887	0,50	5,2
Common electricity	610	1,50	0,1
Heating	24603	1,50	6,1
Insurance	2632	0,50	0,7
Care-taking	14382	0,50	3,6
Other annual cost 1	3047	0,50	0,8
Other annual cost 2	0	0,50	0,0
Periodic maintenance	42228	0,50	10,4
Value at end	-27043	0,50	-6,7
Total	222159		55,1

Present value compilation			
Production	3677632	0,5	912,1
Administration	94165	0,5	23,3
Waste	221221	1,5	54,9
Water and sewage	406967	0,5	100,9
House tax	645592	0,5	160,1
Common electricity	24035	1,5	6,0
Heating	968857	1,5	240,3
Insurance	81352	0,5	20,2
Care-taking	444515	0,5	110,2
Other annual cost 1	94165	0,5	23,3
Other annual cost 2	0	0,5	0,0
Periodic maintenance	1305196	0,5	323,7
Value at end	-835865	0,5	-207,3
Total	7127831		1767,8

APPENDIX C. ENERGY BALANCE CALCULATIONS

Table C.1 Input data

Building structures. Areas and energy related data

Structure	Type	Area	U-value	Air leakage	Glass share/ Transmittance
A1N		m2	W/m2ºC	m3/m2,h	%
Wall North	Light	125,5	0,194	1,6	
Wall South	Light	157,0	0,194	1,6	
Wall East.	Concrete	24,0	0,194	1,6	
Wall West	Concrete	24.0	0,194	1,6	
Wall East.	Light	24,0	0,194	1,6	
Wall West	Light	24.0	0,194	1,6	
Window North		15,7	2	1,6	70/67
Window South		47,2	2	1,6	70/67
Glass door North		16,9	2	1,6	70/67
Door South		16,9	1,50	1,6	
Roof	Light	260,3	0,116	1,6	
Floor on ground	Concrete	224,3	0,234		
Floor on ground	Concrete	36,0	0,360		
Inner wall	Concrete	98,0			
Inner wall	Light	150,0			
Inner floor	Concrete	260,3			
B1N					
Wall North	Concrete	125,5	0,194	1,6	
Wall South	Concrete	157,0	0,194	1,6	
Wall East.	Concrete	48,0	0,194	1,6	
Wall West	Concrete	48.0	0,194	1,6	
Roof	Concrete	260,3	0,116	1,6	
The rest like A1N					
C1N					
Wall North	Light	125,5	0,194	1,6	
Wall South	Light	157,0	0,194	1,6	
Wall East.	Light	48,0	0,194	1,6	
Wall West	Light	48.0	0,194	1,6	
Inner wall	Light	248,0	0		
A1S, B1S, C1S **A2S, B2S, C2S**	As corresponding A1N, B1N and C1N but with north and south reversed				
Data on ventilation systems					
A1, B1, C1	Mechanical exhaust ventilation. Ventilation rate according to design values 25 l/s, flat				
A2, B2, C2, A3, B3	Balanced ventilation with heat exchanger. 18ºC on incoming air. Effectiveness of heat exchanger: 70% Ventilation rate according to design values 25 l/s, flat				

Table C.2 Calculated energy balance results. (kWh/m2, during the year 2000)

	Transmission	Air leaks*	Ventilation	Excess** ventilation	Solar gains	Internal gains	Heat exchange	**Space Heating*** **
A1N	70,8		56,8	1,7	27,9	37,5		**64,0**
B1N	70,7		56,7	0,6	27,9	37,5	0,0	**62,9**
C1N	70,9		56,8	2,9	27,9	37,5	0,0	**65,2**
A1S	76,4		59,3	6,3	51,8	37,5	0,0	**52,8**
B1S	77,1		59,8	3,5	51,8	37,5	0,0	**51,3**
C1S	75,7		58,8	9,5	51,8	37,5	0,0	**54,8**
A2S	79,5	5,5	53,8	9,2	51,8	37,5	28,4	**31,1**
B2S	80,4	5,6	54,3	6,4	51,8	37,5	28,3	**29,9**
C2S	78,6	5,5	53,3	12,4	51,8	37,5	28,5	**32,7**
A3S	79,9	2,8	54,0	9,8	51,8	37,5	28,4	**29,4**
B3S	80,8	2,8	54,5	6,9	51,8	37,5	28,3	**28,2**

* Does not effect energy balance in an mechanical exhaust ventilated building

** Ventilation due to exceeded maximum indoor temperature (28°c)

*** Hot tap water production excluded

APPENDIX D. ENERGY USE LIFE CYCLE APPRAISAL TOOL

Example Life Cycle Energy. Svedala

Consequences of energy use regarding emissions to air, socio economics and costs								
		Energy use	CO2	NOX	SO2	VOC	Socio economics**	Economy
		MJ or kWh*	kg	g	g	g	Euro	Euro
Oil***	MJ		0	0	0	0	0	0
	kWh	530	177	458	770	44	34	36
Electricity, Swed. mix	MJ		0	0	0	0	0	0
	kWh	1835	79	124	82	25	14	102
District heat. Swed. mix	MJ		0	0	0	0	0	0
	kWh		0	0	0	0	0	0
Natural Gas****	MJ		0	0	0	0	0	0
	kWh	6685	1494	1490	18	41	259	371
Sum	**MJ**	**0**						
	kWh	**9050**						
			1750	**2072**	**870**	**110**	**308**	**509**

* Record either as MJ or kWh

** According to Swedish Public Road Authorities publication 1999:170 (SNRA, 1999)

*** Light oil in medium size boiler. Energy contents: 36000 MJ/m3

**** Medium size boiler. Energy contents: 40000 MJ/m3

APPENDIX E. SIMPLIFIED MADA CALCULATION

Alternative	**α**	**β**	**γ**
Life cycle costs	1766	1778	1768
1766	1,000	0,993	0,999
1778	1,007	1,000	1,006
1768	1,001	0,994	1,000
Energy use	6685	6630	6748
6685	1,000	1,008	0,991
6630	0,992	1,000	0,983
6748	1,009	1,018	1,000
Acoustics	1,33	1,33	2,00
Sound class:	B	B	C
1,33	1	1	0,67
1,33	1	1	0,67
2,00	1,50	1,50	1
Thermal comfort	36	12	60
36	1	3	0,60
12	0,33	1	0,20
60	1,67	5	1
IAQ	1,25	1,25	1,25
	Very good	Very good	Very good
1,25	1	1	1,00
1,25	1,00	1	1,00
1,25	1,00	1	1
Functionality	1,00	1,00	1,67
1,00	1	1	0,60
1,00	1,00	1	0,60
1,67	1,67	1,67	1
Weighted values of attributes			
Life cycle costs	0,4 x 1 = 0,4	0,4 x 0,993 = 0,397	0,4 x 0,993 = 0,40
Energy use	0,2 x 1 = 0,2	0,2 x 1,008 = 0,202	0,2 x 0,991 = 0,198
Acoustics	0,08 x 1 = 0,08	0,08 x 1,00 = 0,08	0,08 x 0,665 = 0,053
Thermal comfort	0,04 x 1 = 0,04	0,04 x 3,00 = 0,12	0,04 x 0,60 = 0,024
IAQ	0,08 x 1 = 0,08	0,08 x 1,00 = 0,08	0,08 x 1,00 = 0,08
Functionality	0,2 x 1 = 0,2	0,2 x 1,00 =0,2	0,2 x 0,599 = 0,12
Total	**1**	**1,08**	**0,87**

APPENDIX F. SELECTED ENVIRONMENTAL DATA

Table F.1. Environmental data for the production of Swedish cement 2000. (Cementa, 2001) Cradle to depot including all raw materials and fuels and transports

Emissions to air g/kg	
NOx	1,25
SO2	0,35
CO2	710
Energy use MJ/kg	
Fossil fuel	2,86
Electricity	0,48
Waste fuels	0,90

Table F.2. Environmental data for the production of ready mixed concrete in Sweden 2000. (Björklund, 1996,with data for cement updated according to Cementa, 2001) Cradle to building site.

Emissions to air g/kg	*C25**
NOx	0,29
SO2	0,06
CO2	94
Energy use MJ/kg	
Fossil fuel	0,49
Electricity	0,07
Waste fuels	0,11

**Concrete cylinder compressive strength class (MPa)*

Table F.3. Environmental data for the production of reinforced concrete elements in Sweden.2000. Cradle to building site (Öberg, 2000, with data for cement updated according to Cementa, 2001)

Emissions to air g/kg	*C30/μ=0,60**	*C50/μ=2,92**
NOx	0,45	0,45
SO2	0,13	0,18
CO2	143	193
Energy use MJ/kg		
Fossil fuel	0,90	1,13
Electricity	0,20	0,33
Waste fuels	0,12	0,14

**Concrete cylinder compressive strength class (MPa)/contents of steel (% by weight)*